UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

ASSOCIATION INTERNATIONALE
D'HYDROLOGIE SCIENTIFIQUE

INTERNATIONAL ASSOCIATION
OF SCIENTIFIC HYDROLOGY

ASSEMBLÉE GÉNÉRALE DE TORONTO

3-14 SEPT. 1957

GENERAL ASSEMBLY OF TORONTO

TOME II

EAUX SOUTERRAINES
SYMPOSIUM VÉGÉTATION
SYMPOSIUM ROSÉE

VOLUME II

GROUNDWATER
SYMPOSIUM VEGETATION
SYMPOSIUM DEW

PUBLIÉ AVEC L'AIDE FINANCIÈRE DE L'UNESCO

PRIX : 300 Frs belges

PUBLICATION N° 44

DE L'ASSOCIATION INTERNATIONALE D'HYDROLOGIE SCIENTIFIQUE
SECRÉTAIRE : L. J. TISON
RUE DES RONCES, 61, GENTBRUGGE (BELGIQUE)
GENTBRUGGE 1958

UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

ASSOCIATION INTERNATIONALE D'HYDROLOGIE SCIENTIFIQUE
INTERNATIONAL ASSOCIATION OF SCIENTIFIC HYDROLOGY

ASSEMBLÉE GÉNÉRALE DE TORONTO

3-14 SEPT. 1957

GENERAL ASSEMBLY OF TORONTO

TOME II

EAUX SOUTERRAINES
SYMPOSIUM VÉGÉTATION
SYMPOSIUM ROSÉE

VOLUME II

GROUNDWATER
SYMPOSIUM VEGETATION
SYMPOSIUM DEW

PUBLIÉ AVEC L'AIDE FINANCIÈRE DE L'UNESCO

PRIX : 300 Frs belges

PUBLICATION N° 43 DE L'ASSOCIATION INTERNATIONALE D'HYDROLOGIE SCIENTIFIQUE
SECRÉTAIRE : L. J. TISON
RUE DES RONCES, 61, GENTBRUGGE (BELGIQUE)
GENTBRUGGE 1958

COMMISSION DES EAUX SOUTERRAINES

The subjects selected for discussion by the Commission were as follows: —

1. Methods used in the production of hydrogeological maps, showing the occurrence, quantity and quality of ground water.

2. Outlines of methods for estimating ground-water resources (excluding geophysical methods).

3. Contamination of ground water by saline waters, industrial wastes, mine or oil-well waters, etc.

4. Methods of using radioactive and other tracers to determine direction and rate of movement of ground water.

5. The role of vegetation and cultivation of a catchment in the hydrological cycle.

The last subject was to be discussed at the joint meeting with the associations of Meteorology and Oceanography.

PROCEEDINGS OF THE SESSION OF THE 6th SEPTEMBER, 1957 AT 9 a.m.

Present: Messrs. Sayre (President), Tixeront, Mann, Jr., Stow, Mageed, Abdulla, Suter, Bergstrom, Klaer, Jr., Krul, Durum, Schneider, Glee, Karrow, Linsley, Kohler, Blake, Keller, Walke, Tison, Jr., Maxey, Tison, Schoeller, Sayre, Karrenberg, Grahmann, Nöring, Allard, Wolf, Nahrgang, Richter, Goldschmidt, Lee, Vibert, Geiger, Guilmet, and Buchan (Secretary).

Dr. A. N. Sayre presided over the Opening Session of the Commission, at which the following reports were presented and discussed:—

1. Some remarks on hydrogeological mapping in the Netherlands, by J. I. S. Zonneveld and J. H. Beltman, presented by A. Volker.

2. Groundwater maps for general distribution in Illinois, by R. E. Bergstrom and L. F. Selkregg.

3. A Groundwater map of the Federal Republic Germany. Scale 1/1.000.000, by R. Grahmann.

4. Hydrogeological maps developed in the last years in Geological Surveys of the Federal Republic of Germany, by H. Karrenberg and W. Richter.

The following papers were read in title only:—

5. La Carte hydrogéologique de la région de Casablanca, by L. Monition.

6. Etablissement des cartes hydrogéologiques, by J. Margat.

7. Cartes de la Hongrie indiquant la qualité des eaux souterraines, by Mme L. Szebelledy.

8. Hydrological maps as a basis in estimating aquiferosity of underground waters resources, by M. B. Churinov.

Discussion:

Report by Messrs. Zonneveld and Beltman

Dr. Goldschmidt asked how long wells were allowed to rest to ensure that a true rest water level could be measured.

Prof. Krul replied that for the archives of ground-water levels in the Netherlands observation wells have been chosen at localities where they would not be influenced by pumping from neighbouring wells.

In response to a further query by Dr. Goldschmidt about the adequacy of maps for showing ground-water levels in areas where pumping has disturbed the static ground-water level, Dr. Sayre said that in the United States they used contour lines to show the decline of ground-water levels during specified periods, usually one year. With such maps it was possible to determine the rate at which the aquifer was being depleted.

Dr. Buchan: «How is it proposed to show on the maps areas where the water level is rapidly falling?»

Mr. Volker: «Maps showing ground-water levels in areas affected by pumping should be revised periodically. Reference to the fall of levels could be given in an explanatory note forming part of the map and profiles.»

Report by Messrs. Bergstrom and Selkregg

Dr. Buchan referred to the absence of definitions of the quantitative terms used on the maps and emphasized the need to explain what was meant by terms such as «poor» and «good». He pointed out that what was «good» for a village might be very «poor» for a town.

Dr. Maxey: «The legend on availability is more fully explained in the text. The terms are meaningful within the limitations of this study.»

Dr. Maxey also mentioned that maps such as those described are available upon request from the Illinois Geological Survey, Urbana, Illinois.

Dr. Sayre: «Dr. Buchan is correct in stating that values should be placed on such terms as «good», «excellent», etc. I suspect that the workers in Illinois have done so in their own minds. However, the adequacy of data and the variability of formational permeability and transmissibility requires that until test drilling has been completed these values are at best only estimates.»

Mr. Bergstrom: «Dr. Sayre is correct. We have placed approximate values on the descriptive terms used in our reports. Although we are restrained by our operating code from predicting well yields. The purpose of the map is to outline areas for exploration and hydrological evaluation which should precede any other ground-water development.»

Professor Krul «I think that the first thing to do is not to make a map but to collect data and to make it available at a central agency. I, therefore, agree with the author that a geohydrological map should supply only general information of a qualitative character and that quantitative information on local questions should be furnished by geo-hydrological institutions.»

Mr. Bergstrom; «In Illinois we have been collecting such data at the Geological

Survey and at the Water Survey for over 35 years. More than 170,000 sub-surface records are filed at the Geological Survey alone. We prepare upon request many hundreds of reports on ground-water conditions at specific sites in Illinois each year. This service supplements the ground-water circular programme.»

Report by Professor Grahmann

Dr. SAYRE asked where the maps which Professor GRAHMANN showed could be obtained.

Professor GRAHMANN: «They may be bought in the Spring of 1958 from: BUNDESANSTALT FUER LANDESKUNDE, REMAGEN, RHINELAND, GERMANY.»

PROCEEDINGS OF THE SESSION OF 6th SEPTEMBER, 1957 AT 2 p.m.

Present;— Messrs. KRUL (Vice-President). KARRENBERG, GRAHMANN MAXEY WILM, TISON, Jr., TIXERONT, BERGSTROM, BUHLE, MANN, Jr., KLAER, Jr., SCHNEIDER, RODIER, SCHOELLER, VIBERT, TISON, FRIEDRICH, GBERARDELLI, STOW, GEIGER, OSMAN, BARTLET, GOLDSCHMIDT, NAHRGANG, NORING, VOLKER and BUCHAN (Secretary).

Professor W. F. J. M. KRUL presided over the Second Session of the Commission at which the following reports were presented and discussed:—

1. Methods of drawing hydrogeological maps, developed in the last years in Western Germany, by F. NORING.

2. Exemple d'une carte hydrogéologique pour un but spécifique, by A. VOLKER.

The following papers were read in title only:—

3. Types of hydrochemical maps in hydrogeology, by A. I. SILIN-BETCHURIN.

4. Présentation de la carte hydrogéologique de la Plaine des Triffas (Maroc Oriental), by F. MORTIER.

5. Classification of underground waters resources and their plotting on maps, by G. V. BOGOMOLOV and N. A. PLOTNIKOV.

6. Hydrogeological maps of mountain folded regions and their significance in estimating resources of underground waters, by A. M. OVCHINNIKOV.

DISCUSSION:

Report by Dr. Nöring

Dr. MAXEY: «How do you detect small but linearly long and more or less «hidden» springs and how do you relate them to specific recharge areas?»

Dr. NÖRING: «When a spring has a flow of any significance it must appear in a surface watercourse where it can be measured. The recharge area can be estimated when all the data has been assembled.»

Professor MANN: «How do you propose to measure the spring and stream flows?»

Dr. NÖRING: «By current-meter, weir, measuring vessel, measurement of flow-velocity or by estimation.»

Mr. SCHNEIDER: «Has the programme of measurement of spring flow progressed far enough to be used in estimating or computing permeability or transmissibility of the shallow aquifers?».

Dr. NÖRING: «No. It will begin in September, 1957.»

Dr. GOLDSCHMIDT: «How do you ascertain the underground catchment of the springs?»

Dr. NÖRING: «Approximate boundaries of catchment areas can be estimated when all the available information about quantity, fluctuation, chemistry and altitude of springs is related to precipitation, soil structure, vegetation and geology of the areas.»

Report by M. Volker

M. VIBERT: «Bien que la question soit quelque peu en dehors du sujet, je serais reconnaissant à M. VOLKER de bien vouloir indiquer les conséquences qu'il a tirées de son étude en ce qui concerne l'incidence éventuelle du'une variation du niveau du lac (abaissement) sur celui de la nappe phréatique riveraine.»

M. VOLKER : « L'assèchement d'un polder dans le lac le long de la zone côtière considérée pourra en effet causer un rabattement de la nappe phréatique dans cette zone. En cas d'une soudure directe du polder à la zone côtière, le rabattement sera tellement grand (jusqu'à 1.0 mètre) qu'il en résultera des baisses de rendement agricole considérables. On a donc séparé le nouveau polder de la ligne côtière par un lac de bordure, d'une largeur de 2600 mètres au maximum. Le niveau de ce lac sera un peu plus élevé que le niveau avant l'asséchement, afin de donner une contre-pression.»

M. TIXERONT : « Quelle est l'épaisseur de la couche semi-perméable.»

M. VOLKER : « La couche semi-perméable est assez mince : l'épaisseur varie entre 1 et 3 mètres. Mais il existe d'autre couches semi-perméables à plus grandes profondeurs, notamment une couche d'argile de quelques mètres à une profondeur de 15 mètres. L'on distingue très bien cette dernière couche dans la carte des résistances, trouvée par division des données des deux autres cartes géohydrologiques.»

Dr. MAXEY: «How did the results of examination of the geology, logs, etc., compare with the results of your determinations, especially in relation to distribution of the less permeable material.

M. VOLKER: «It was found that zones with high resistances could be correlated with the occurrence of thicker semi-pervious layers and clay layers below the surface. Nevertheless, to get quantitative data one has to make numerical measurements such as the determination of piezometric heads, rate of seepage by base flow, measurement of the rivers, etc. It is not possible to gather such data by collecting only geological information, well logs, etc.»

PROCEEDINGS OF THE SESSION OF 7th SEPTEMBER, 1957 at 9 a.m.

Present: Messrs. ALLARD, VOLKER, WOLF, NORING, NAHRGANG, GOLDSCHMIDT, SUTER, THYSSE, KARRENBERG, GRAHMANN, KRUL, TISON, MAXEY, TISON, Jr., SCHOELLER, SAYRE, STOW, MAGEED, ABDULLA, RICHTER, BUHLE, VILELA, BERGSTROM, SCHEIDEGGER, SELKREGG, SCHWARZ, SCHNEIDER, BLANEY, DURUM, ALEXANDER, GLEE, VIBERT, REMENIERAS, ROBINSON, SCHIFF, MANN, Jr., WILSON, LAMBOR, RODIER GBERARDELLI, SACHS, BLAKE, OSMAN, CHOW, SERRA, LINSLEY, TIXERONT, STICHLING, HAMILTON and BUCHAN (Secretary).

Prof. H. SCHOELLER presided over the Third Session of the Commission at which the following reports were presented and discussed:—

1. A scale model, based on the viscous flow analogy, for studying groundwater flow in an aquifer having storage, by G. SANTING, presented by W. F. J. M. KRUL.

2. Estimating quantity and quality of ground-water in dry regions using airphotos, by John F. MANN, Jr.

3. Détermination de la quantité d'eau utilisable de la nappe souterraine démontrée par l'exemple d'une grosse évacuation dans une région étendue, by Gunther NAHRGANG.

4. The quantitative approach to ground-water investigations, by J. G. FERRIS and A. Nelson SAYRE.

The following papers were read in title only:—

5. Elements pour l'établissement du bilan de la nappe phréatique des Triffas, by F. MORTIER.

6. Principles of the regional estimate of natural resources of underground waters and problems of water balance, by B. I. KUDELIN.

DISCUSSION:

Report by Mr. Santing

M. REMENIERAS : « Quelle est la nature du liquide visqueux employé pour obtenir une bonne stabilité de ses propriétés avec le temps et la température etc? Quel est le nombre de Reynolds limite admissible (compte tenu des aspérités dues aux jonctions des tubes piezométriqucs, des variations de l'épaisseur entre plaques, tenant compte des différences de perméabilité etc.) pour que le régime de l'écoulement reste laminaire?»

Prof. KRUL : « *a*) On connaît plusieurs liquides bien utilisables comme le glucose, la paraffine liquide, la glycerine, l'huile lubrifiante. Ces liquides ont une bonne stabilité de leurs propriétés physiques avec le temps; il n'y a que leur viscosité qui change avec la température. On doit en tenir compte pendant les expériences. D'autre part les essais sont faits dans un laboratoire de température presque constante. *b*. Le nombre de Reynolds limite est de 1000 environ. Dans tout le modèle l'écoulement reste laminaire.»

Dr. SAYRE: «What arrangement do you provide to ensure constant separation between the two plates of the model? Unless posts are provided to maintain constant separation the results will be erratic.»

Professor KRUL: «The separation is kept constant by a great many posts between the two plastic plates.»

Mr. SCHNEIDER: «What were the results of introducing fluids of different colours representing salt-water intrusion?

Prof. KRUL: «The general principle of the introduction of fluids of different density and different colours was described in a paper by Mr. SANTING presented at Brussels at the I. U. G. G. Meeting (Modèle pour l'étude des problèmes de l'écoulement simultané des eaux souterraines douces et salées). The salt water intrusions could be studied effectively.»

Prof. SCHOELLER : « Quelle est l'importance de l'influence de l'entrée latérale du liquide par un tube étroit alors qu'une entrée normale se fait sur toute la hauteur de la nappe.»

Prof. KRUL : « En effet, il existe une influence locale à l'entrée du liquide par un tube étroit. A petite distance de l'entrée cette influence ne se fait plus sentir.»

Mr. WOLF: «The models are based on a theory which includes certain idealisations, the data fed into the models have again been idealised, the results obtained will not, therefore, exactly correspond to the details of prototype behaviour. Minor simplifications of model technique, such as introduction or withdrawal of the liquid at a point rather than along a line will cause local distortions without affect the broad overall picture more than the basic simplifying assumption.

Mr. WOLF reminded the Commission that the English word »Paraffin» corresponds to the American «Kerosene.»

Dr. NAHRGANG : «Le rabattement de la surface libre et la variation de la surface phréatique sont négligés dans le modèle de M. SANTING. Et c'est pourquoi les résultats obtenus avec ce modèle ne sont pas exacts, s'il y a une grande influence de la variation de l'épaisseur de la couche perméable causée par l'écoulement.»

Prof. KRUL : « Le modèle est basé sur la condition que les variations de la surface phréatique sont très faibles en comparaison de l'épaisseur de la couche aquifère. Si cette condition n'est pas remplie, ce type de modèle n'est pas utilisable.»

M. TISON, Jr. : « Avez vous eu l'occasion de comparer les résultats donnés pour ce modèle avec les résultats d'un autre modèle, plus classique, de la même région?»

Prof. KRUL : « Non. Mais avant de construire le modèle définitif, on a développé un petit modèle d'essai de ce type, afin d'étudier quelques problèmes simples concernant l'écoulement de l'eau souterraine (par exemple le rabattement de la surface phréatique par pompage par un puits situé au centre d'une île circulaire). Les résultats de ces essais s'accordaient d'une façon satisfaisante avec les résultats des calculs.»

Dr. MAXEY: «Can you give us some idea of the amount of information you used to make your determinations in the Zealand Flanders area?

Professor KRUL: «At several places of the catchment area pumping tests were made, whereas hundreds of pumping wells and observation wells made it possible to know the thickness of the water-bearing layer and the transmissibility. Further data of the groundwater levels in the observation and pumping wells and rainfall data were available for a great many years.»

Dr. MAXEY: «Is the assumption made than an aquifer is homogeneous and isotropic with infinite area?»

Professor KRUL: «The aquifer in Zealand Flanders is assumed to be homogeneous and isotropic. Whether it is of finite or infinite extent is of little importance, since only part of its areal extent is represented in the model. The conditions at the boundaries of that part, e.g. the groundwater fluctuations, should of course be limitated in the model.»

Mr. SCHNEIDER: «Have any practical applications been made in the area concerned?»

Professor KRUL: «The report and recommendations have been made so recently that there has not been time to check the validity of the recommendations.»

Report by Dr. Nahrgang

M. VIBERT : « Prie le conférencier de lui expliquer les raisons pour lesquelles les courbes d'égal abaissement du niveau de la surface libre de la nappe phréatique, sont fermées extérieurement au captage au lieu de se fermer autour du captage. M. VIBERT remercie le conférencier après que celui-ci lui a fait connaître qui cette « anomalie apparente » provient du fait que les mesures permettant l'établissement des dits courbes ont été effectuées après un ralentissement notable de la cadence des pompages.»

Report by Messrs. Ferris & Sayre

Professor KRUL: «I know that a staff of hydrologists—about 530— is working under the direction of Dr. Sayre in different areas of the United States of America. I would like to know whether the special scientific work (model research, statistics, mathematics, etc.) is handled at one or more central laboratories or if the work is decentralized in regional branches.»

Dr. SAYRE: «The United States Geological Survey has a laboratory and a staff of geologists, physicists, mathematicians, and engineers working on research problems

in Washington, D.C., and Denver, Colorado. Several scientists are also working at detached posts in other parts of the country, studying glacial geology, salt-water encroachment, land subsidence, radio-activity, etc. The staff investigating ground-water problems also carries out pure research in the course of their investigations. For example C. V. THEIS, who is now engaged on the study of disposal of radio-active wastes, developed his non-equilibrium fromula while acting as District Geologist in New Mexico.»

M. TIXERONT : « M. SAYRE a insisté à la fin de son exposé sur l'importance des données géologiques. Je pense que les géologues devraient se préoccuper de fournir des données quantitatives et non seulement qualitatives. Dans cet ordre d'idée, je note que M. SAYRE ne nous a pas parlé des méthodes de prospection géophysiques. Je voudrais lui demander quelle est son opinion à ce sujet. J'ai utilisé ces méthodes, et particulièrement la méthode de résistance électrique et il me semble qu'elles ont fait de grand progrès au cours des dix années passées.»

Dr. SAYRE: «The United States Geological Survey has used electrical resistivity in connection with its ground-water studies for over 25 years. The Illinois Geological Survey has also used it with considerable success for more than 25 years. Several consultants likewise use it in their work. I did not refer to it in my paper because I considered it to be a tool for exploration rather than a quantitative method for estimating ground-water resources. It is true that many geologists are not adequately trained in mathematics to develop new formulae for quantitative estimation of ground-water. However, most of those working on ground-water problems are quite capable of using the mathematics in their work and some have made substantial contributions, for example, C. V. THEIS and M. KING HUBBERT. Moreover, American Universities in the course of training geologists emphasize mathematical and physical training, both in undergraduate and graduate schools.

PROCEEDINGS OF THE SESSION OF 9th SEPTEMBER, 1957 AT 9 a.m.

Present: Messrs. KRUL, THYSSE, SCHNEIDER, TISON, MAGEED, ABDULLA, RICHTER, VILELA, STOW, ROBINSON, BLANEY, TISON, Jr., GEIGER, TIXERONT, BLAKE, BARTLET, SCHIFF, MANN, Jr., MAXEY, BUHLE, BERGSTROM, SELKREGG, DEUTSCH, VOLKER, KARRENBERG, NAHRGANG, NORING, DURUM, HARBECK, VIBERT, AYRES, WITHERSPOON, HORE, SKIBITZKE, SUTER, POLLITT and BUCHAN (Secretary).

Mr. A. N. SAYRE presided over the Fourth Session of the Commission at which the following reports were presented and sicussed:—

1. Determination of the geohydrological constants for the dune-water catchment of Amsterdam, by L. HUISMAN, presented by G. J. DE GLEE.

2. Movement of underground water below and above the phreatic level, by P. C. LINDENBURGH, presented by W. F. J. M. KRUL.

3. The use of filters to increase infiltration in aquifers for ground water recharge, by L. SCHIFF.

The following papers were read in title only:—

4. A field method for measuring the permeability of unsaturated sands and sandstones, by N. S. BOULTON and G. S. DHILLON.

5. Estimate of the subterrenean water resources of Carstic Regions, by H. KESSLER.

6. Determination of permeability by pumping from a spherical well, by T. ONODESA.

Discussion:

Report by Dr. Lindenbergh

Mr. Schneider: «What temperature controls were used in the rainfall infiltration experiments?»

Professor Krul: «No close controls were used, but the experiment was not subjected to any extreme changes as the apparatus was set up in a closed building.»

Mr. Robinson: «Was the 2.5% difference between de-watering after saturation and by saturation from above due entirely to air within the pores or could part of it be the result of a thicker film of water around the sand grains?»

Professor Krul : « Dr. Lindenbergh states in his paper that former investigation had demonstrated that 2.5% of the pores were filled by air. The new experiment was in accordance with former experience.»

M. Schoeller : « Comment a-t-on tenu compte de la frange capillaire qui doit se produire au fond des appareils, en particulier au fond de l'appareil de mesure de la vitesse d'infiltration ?».

Prof. Krul : « Il ne peut y avoir une frange capillaire d'une hauteur importante au dessus des couches drainantes sur le sol du cylindre. Il est permis de concevoir la masse entière de sable comme une zone non saturée.»

Dr. Nahrgang : « Il me semble vraisemblable, que la vitesse de suintement n'est pas constante mais qu'elle dépend de l'épaisseur de la zone remplie d'eau. Si l'épaisseur est plus petite que la frange capillaire, il n'y a pas d'écoulement, c'est-à-dire la vitesse $v = 0$. Et l'autre limite est celle que l'épaisseur du milieu poreux où les pores sont remplis d'eau est beaucoup plus grande que la frange capillaire : maintenant la vitesse atteint la perméabilité K.»

Prof. Krul : « La vitesse mentionnée dans la communication de M. Lindenbergh ne se réfère pas à l'écoulement par une zone saturée mais par la masse de sable non saturée au dessus du niveau capillaire. Dans la couche supérieure du sous-sol des bassins d'infiltration il se forme, immédiatement après le replissage du bassin, une zone presque saturée, d'une épaisseur de quelques décimètres. Au-dessous de cette zone, se trouve la masse de sable non saturée, avec une teneur en eau de 7 à 11%. L'eau de la couche supérieure s'infiltre lentement par cette masse de sable non saturée. La vitesse moyenne de l'écoulement par cette masse est mesurée par le passage d'une eau colorée.»

Professor Mann: «I understand that the 16 cm/day is the average velocity vertically downward through the sand. In Californian dune sands of comparable grain size we get infiltration rates at least 10 times 16 cm/day. I believe that additional field experiments in the dunes of Holland will show that much higher infiltration rates will be obtained.»

Professor Krul replied that the rate of flow of 16/cm/day is the experimentally measured velocity of vertical penetration of rain water, originating from heavy showers, through the non-saturated dune sand above the capillary zone.

Professor Krul offered to invite Dr. Lindenbergh to send more particulars to Professor Mann.

Mr. Skibitzke: «Water travels through pore spaces at varying rates. The most rapid rate is in the centre of the pore spaces, but diffusion tends to eliminate this as a function of distance of travel. What function of the maximum rate of travel do you use to determine the average rate of flow?»

Prof. Krul: «The average rate of flow was measured by determining the time in which coloured water travelled through the cylinder.»

Dr. SUTER remarked that in veiw of his experience in Peoria where the loss of capacity was only 15% in seven months he was surprised at Mr. SCHIFF's lack of success in using a pea gravel.

Dr. SUTER: «The increase of capacity of flow through the bottom of the pit is not fundamental to artificial recharge. The ground beneath the pit is soon saturated. After only as much water can recharge as can flow away laterally, no matter what the capacity of infiltration of the pit bottom. Suitable geometric form of pit is very important for a high rate of recharge.»

Mr. SCHIFF: «Under the conditions reported, water suspended load and other characteristics rendered a 6 inch layer of 1/4 inch pea gravel over aquifer material ineffective as a filter to increase infiltration rates. Greater depth and length are both conducive to increasing lateral flow and thus the infiltration rate. Shallow sand layers at Bakersfield, California, start about 6 feet beneath the soil surface and are 4 to 8 feet in thickness. The sides of the pit exposed about 750 square feet of the 1500 square feet of aquifer material exposed. The overall dimensions of the exposed aquifer is 20 feet $\times$ 75 feet. When the maximum rate of infiltration occurred (an average of 58 feet per day) a good part of the daily total flow moved through the sides of the pit. However, clay particles, carried by the water at such a high velocity, moved through the pea gravel and deposited on *both* the sides and bottom of the pit. In about 60 days the infiltrated rate dropped to 32 feet per day. Scraping restored the infiltration rate.

A sound filter with particle sizes ranging from 0.5 to 1.6 mm and another filter composed of small, sharp, angular grits gave much higher infiltration rates into aquifer material than either 1/4 or 1/8 inch pea gravel in infiltrometers for conditions similar to those under which the pit operated.

It may be that in the Peoria pit electrolytes, and temperature or other factors, are causing flocculation and the considerable sedimentation that occurs on top of the 1/4 inch pea gravel or at shallow depths. Fortunately considerable porosity remains.

A filter is needed that will distribute clogging soil particles through a depth to maintain porosity and yet permit cleaning by suction or scraping. In final analysis the depth of pits or trenches, amounts injected, maintainance costs and benefits must be evaluated.»

PROCEEDINGS OF THE SESSION OF 11th SEPTEMBER, 1957 AT 9 a.m.

Present: Messrs. NORING, NAHRGANG, BARTLETT, SUTER, BLAKE, MANN, Jr., BERGSTROM, GEIGER, TISON, VIBERT, SCHOELLER, SCHEIDEGGER, BUHLE, WATT, PREST, DURUM, TISON, Jr., MAXEY, SCHNEIDER, SKIBITZKE, GRAHMANN, RICHTER, VILELA, KRUL, SELKREGG, DEUTSCH, SCHIFF, SAYRE, POLLITT, OSMAN, ABDULLA, HORE, DOLAR-MANTAUNI and BUCHAN (Secretary).

Professor W. F. J. M. KRUL presided over the Fifth Session of the Commission at which the following reports were presented and discussed:—

1. Status of ground-water studies in Canada, by J. F. CALEY and K. POLLITT.
2. Correlation of ground water levels and air temperatures in the Winter and Spring in Minnesota U. S. A., by R. SCHNEIDER.
3. On the theory of flow of miscible phases in porous media, by A. E. SCHEIDEGGER.

4. The use of radioactive tracers in hydrologic field studies of ground-water motion, by H. E. SKIBITZKE.

The following papers were read in title only:—

5. A hydrological survey in British Honduras, by C. G. DIXON.

6. Laws of formation of underground run-off and methods of conversion into open reservoirs and rivers, by F. A. MAKARENKO.

7. Exploratory drilling for groundwater in the Narmada Valley, India, by A. K. RAY.

8. Ground water control in the Neyveli lignite field South Arcot District. Madras, by G. C. CHATERJA, V. SUBRAMANYAM and P. H. JONES.

9. Studies on the groundwater conditions of the Mahendragarh District, India, by G. C. CHATERJI and A. B. BISWAS.

DISCUSSION:

Report by Messrs. Caley & Politt

Professor KRUL asked for particulars about the Water Drillers Act and its operation in the Province of Ontario.

Mr. WATT: «Under the Ontario Water Resources Commission Act now in effect and Regulations made under the authority of the former Water-well Driller's Act, all water well drillers must carry a licence which we issue to them. It is renewed annually but we will not renew it and may cancel it if the driller does not send in hydrological and geological data on a form that we supply for all the wells he drills. Two field inspectors help the drillers to fill out the forms the way we want or gather court evidence for us in case we decide to force the driller to conform through court action. In ten years we have had about 10 court cases. The drillers themselves would like more teeth in the Act. They use the data we are assembling more than any other group.

Report by Mr. Schneider:

Mr. SCHEIDEGGER: «Have any quantitative estimates been made? For example has the time taken for a temperature change in the air to be felt at the bottom of the frozen layer been made?»

Mr. SCHNEIDER: «No».

Mr. SCHEIDEGGER: «If this were done it would greatly enhance the value of the communication.»

Professor SCHOELLER asked if the author had taken into consideration the velocity of propagation of cold and hot waves in the soil.

Mr. SCHNEIDER: «No. The instrumentation was not adequate to permit this possible refinement in the quality of the data collected.»

Mr. ROBINSON: «Did you observe any diurnal fluctuations resulting from differences in temperature?»

Mr. SCHNEIDER: «No, any possible diurnal fluctuations may have been masked by interference from two nearby pumping wells.»

M. VIBERT prie le conférencier de bien vouloir lui faire connaître s'il n'a pas constaté un certain déphasage plus ou moins systématique mais variable dans le temps entre le minimum et maximum de la courbe des niveaux d'eau de la nappe et ceux de la courbe des températures.

Mr. SCHNEIDER: «The rise in water level in response to a rise in the temperature in the Winter and Spring follow the temperature by two or three days.»

M. TISON : « Dans une étude présentée à Rome G. TISON a mis en relief une autre action des variations de température sur le niveau de l'eau des puits dans une nappe peu profonde (1 pied sous le niveau du sol). Une augmentation brusque de la température correspond à une diminution de la hauteur de la zone capillaire. Mais d'autre part, le volume total de l'eau de la nappe y compris celui de la zone capillaire reste sensiblement constant. La diminution de la hauteur de la zone capillaire doit par conséquent se traduire par une hausse de la nappe proprement dite et par conséquent du niveau de l'eau dans les puits de cette nappe ».

Mr. SCHNEIDER agreed that this could be a factor, but did not apply to his present study.

M. TISON, Jr.: «Was any influence observed of change of air temperatures on ground-water levels during the Summer when the soil was not frozen?»

Mr. SCHNEIDER: «During the Summer the trend of the water table is downward due largely to evapo-transpiration and the phenomena described in this paper were not observed during this season.»

Mr. ROBINSON: «In desert areas with shallow water table where the temperatures are many degrees above freezing, I have observed on at least three occasions responses of water level in a well due to changes in air temperatures. As the air temperature decreases the water level decreases and vice versa. This I have attributed to the viscosity of the water which varies inversely with changes of temperature. For a discussion of this phenomena see the United States Geological Survey Water Supply Paper 1103.»

Prof. MANN: «It is amazing to me that the air temperature, because of the melting of the base of the frozen soil, could produce a reaction in only a week. Maximum heat conduction would take place through the well casing, perhaps thawing first the soil surrounding the casing. Thus surface water could be funneled downwards along the casing to produce a local rise of water level in the well.»

Mr. SCHNEIDER: «The phenomena described were observed even when a heavy snow cover insulated the casing to a certain extent. Should the casing conduct heat to the surrounding soil and thus produce a local rise or «mound» on the water table, the «mound» would quickly dissipate by rapid lateral and downward movement because of the relatively high permeability of the aquifer.»

PROCEEDINGS OF THE SESSION OF 11th SEPTEMBER, 1957 AT 2 p.m.

Present: Messrs. VOLKER, NÖRING, RICHTER, GRAHMANN, KRUL, SCHOELLER, SCHNEIDER, MAXEY, SELKREGG, PREST, WATT, DURUM, VILELA, THIRLAWAY, BARTLETT, TISON, ROBINSON, MANN, BUHLE, BERGSTROM, NAHRGANG, VIBERT, THYSSE, OSMAN, BLANEY, SCHIFF and BUCHAN (Secretary).

Professor H. J. SCHOELLER presided over the Sixth Session of the Commission at which the following reports were presented and discussed:—

1. Essai d'explication de constatations faites sur les variations de salinité de certaines eaux du sous-sol bruxellois, by G. TISON.
2. Contamination of ground water by soil wells, by F. NÖRING.
3. La salinité des eaux artésiennes en Belgique du Nord, by L. TISON.
4. Pollution of ground-water, by J. K. BAARS and H. J. BOORSMA, presented by W. F. J. M. KRUL.
5. Pollution of ground-waters by oil fields wastes in Southern California, by J. F. MANN.
6. Drawing both fresh and salt water from one pumping-well divers, by G. SANTING, presented by A. VOLKER.

The following papers were read in title only:—

7. Décontamination de la nappe phréatique de Skhrirat envahie par du kéronèse, by R. AMBROGGI, E. DE GELIS and L. MONITION.

8. Possibilité du tirage d'eau douce des nappes soutenues par des eaux saumâtres, by L. ZORI.

DISCUSSION:

Report by Professor Tison

M. VIBERT : « Pour corroborer les indications générales. données par M. TISON au début de son exposé, je me permets de signaler que des considérations semblables à celles indiquées par M. TISON, concernant les nappes de son pays. ont été faites sur les nappes profondes du Bassin Parisien : Albien et Aptien notamment. Des eaux prélevées dans ces nappes, dans des forages voisins l'un de l'autre, mais a des profondes différentes, ont donné, à l'analyse, des résultats sensiblement différents et par suite des degrés hydrotimétriques également différents. Aucune explication de ces différences n'a été donnée jusqu'à présent. On peut penser que la théorie développée par M. TISON est de nature à faciliter la solution de ce problème.»

Report by Messrs. Baars and Boorsma

Mr. SCHIFF: «This comment concerns the additional value of such studies from the standpoint of the incorporation of organic residues to improve soil structure and the stability of soil structure. Microbic conditions produce the less soluble gases mentioned which retard infiltration water during the decomposition process.

As complete decomposition is approached and drying of microbial secretions takes place, infiltration rates have been increased appreciably. These coatings surround and improve the structure of soil particles. They seem quite resistant to further attacks by other microorganisms. They also seem to reduce the friction of soil to water movement.

The addition of hydrocarbons have improved soil structure and thus increased infiltrates, however, the longevity of the effect of such chemical treatments have not been as long as those produced by organic residues. Further investigations are needed on benefits derived from aerobic and anaerobic conditions.»

Prof. KRUL: «In adding hydrocarbons to the soil for improving soil structure one has to be very careful as these hydrocarbons often contain components which may cause a bad taste in ground water which might be needed for drinking purposes. Whether these organic components will be oxidised completely in the superficial layers or not, has to be controlled thoroughly in advance of application.»

Report by Messrs. Mann and Stone

Dr. SAYRE: «Pollution of ground water by saline and other waste products of industry is a serious problem in many parts of the United States. State after State is passing legislation requiring strict controls of waste water, both in streams and underground water reservoirs. To the problems mentioned by Dr. MANN we are on the threshold of a new pollutant—namely the wastes of atomic energy plants. We hope that before this programme becomes widespread we will have done enough research to enable us to advise the technical people on matters pertaining to safe disposal of long-lived isotopes.»

Mr. SCHIFF : «The approach in California to-day appears to be a cooperative one between the State Pollution Board, the California State Department of Water

Resources and the Oil Companies. Available information and investigations leading to information on the effect of geological conditions, hydraulic gradients and the hydraulic conductivities of the various soils involved are sought. Such information is then used to dispose of contaminated water with the reasonable assurance that it will flow vertically downward and/or laterally to such locations that will cause no problems.»

M. TIXERONT demande à l'auteur s'il peut donner quelques renseignements sur les effets des eaux résiduaires des papeteries sur les eaux souterraines.

Prof. MANN: «We have no experience with this problem as there are no such industries in southern California.»

Report by M. Santing

Prof. MANN: «I gather that this well is in a special situation, as this type of pumping is generally not to be recommended. It would be better to have a group of widely spaced wells, each of low capacity.»

M. VOLKER: «I agree. The method described is useful in case of a limited catchment area out of which the maximum fresh water has to be withdrawn. The general water balance will finally be decisive.

PROCEEDINGS OF THE SESSION OF 11th SEPTEMBER, 1957 AT 4 p.m.

Present: Messrs. VOLKER, KRUL, RICHTER, NÖRING, NAHRGANG, MANN, ROBINSON, SKIBITZKE, BUHLE, BERGSTROM, VIBERT, TIXERONT, OSMAN, DURUM, GBERARDELLI, SELKREGG, MAXEY, SCHNEIDER, SCHOELLER, SAYRE and BUCHAN (Secretary).

Dr. SAYRE presided over a special meeting called to review the work of the Commission and to make suggestions for its future.

Although two sessions had been devoted to a useful exchange of ideas about methods of presenting geo-hydrological information in map form, those present felt that the subject is sufficiently important to justify further study before any attempt is made to standardize methods. A proposal that work should be continued over the next three years and results presented at the next Assembly was agreed. The Commission also recommended that maps should be exhibited on that occasion with a view to encouraging the production not only of national maps but of interstate or international maps.

A request was made that corresponding members of countries in which geo-hydrological maps were published should send a list including the price of purchase to the Secretary for the information of all interested.

The Commission also agreed that methods of estimating ground-water resources, which were discussed at two sessions, had not been exhaustively examined and recommended further study.

As only one paper had been submitted on the use of radioactive isotopes, the Commission felt that the subject may have been introduced prematurely. In view of the growing interest in radioactivity it was agreed that further time be devoted to study and that results should be submitted at the next Assembly.

Several members asked about the possibility of distributing copies of papers before meetings to facilitate discussion. While all were agreed that this would be desirable, it was accepted that the finances of the Association are not strong enough to allow distribution of pre-prints. The Commission recommended that authors

should be asked to provide 50 duplicated copies of their papers for distribution before the next meeting.

It was also agreed that each country should be invited to provide the Secretary of the Commission, for circulation among its members before the next Assembly, a list of the institutions engaged in scientific ground-water research, together with the names of workers and the nature of their current research. This is intended to assist contact between workers with mutual interest.

The proceedings of the Commission were then concluded.

The following subjects for discussion by the Underground Waters Commission at the next Assembly were announced at a full meeting of the Association:

1) Methods of presenting geohydrological data in map form (maps, especially feose based on new methods, may be exhibited).

2) Methods of estimating ground-water resources.

3) Radioactive substances:

a) their experimental use in ground-water studies and

b) the hydrology of their disposal into pervious strata.

4) Saline infiltration into aquifer in coastal and estuarine areas.

SOME REMARKS ON GEO-HYDROLOGICAL MAPS FOR THE NETHERLANDS (*)

ZONNEVELD & BELTMAN

ABSTRACT

For areas as the Netherlands, which for their larger part and built up of different, rather thick layers of sediments, it proves difficult to represent all the desired geo-hydrological data of all the layers on one map only. Such a map soon becomes too overcrowded with symbols and colours to be legible. Moreover gradual changes with depth of certain properties (e.g. the chlorine content of the groundwater) are difficult to represent.

It seems therefore more suitable to draw a series of maps whereby the following possibilities occur.

a. for each geological horizon a map is drawn, either with or without contourlines of top- and bottomsurface or isopachs. On each of this maps all the geo-hydrological data of the horizon concerned or the data of only one or more elements (e.g. the chlorine content, the hardness of the groundwater etc.) can be represented.

b. on each map all the geo-hydrological data or the data of only one or more elements are represented for one of a series of consecutive levels (e.g. 0-10 m, 10-25 m, 25-50 m etc., with regard to O. D.)

Besides these series of map geo-hydrological profiles are indispensable. They have the advantage that gradual changes with depth of certain properties can easily be represented. Series of parallel profiles in two more or less perpendicular directions seem te be the most suitable.

Some of the above-mentioned possibilities of maps and profiles are illustrated with an example.

For areas like the Netherlands, which for a greater part are built up of different, rather thick layers of sediments, it proves difficult to represent all the desired geo-hydrological data of all the layers on one map only. Such a map soon becomes too crowded with symbols and colours to be legible. Moreover gradual changes with depth of certain properties (e.g. the chlorine-content of the groundwater) are difficult te represent. It therefore seems more practical to make several maps, each representing geo-hydrological data of only one or a few different kinds. Besides such maps profiles will prove valuable, especially to show changes of certain properties with the depth.

In the Netherlands a new geological map is in course of preparation by the Geological Foundation. This map will include geo-hydrological maps and profiles in accordance with the above-mentioned principle.

This principle may be demonstrated for the following maps, charts and profiles, which in the course of time have been made for special purposes.

Plate 1. Chart of the chemical composition of the groundwater in the province of Zeeland.

The chart shows the chemical composition of the groundwater in borings in the province of Zeeland, represented in coloured diagrams and expressed in % millival, the total sum of positive ($Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, $K^{\cdot\cdot}$, and $Na^{\cdot\cdot}$) and negative ions (HCO'_3, SO''_4, and Cl') being 100 %.

The total amount of millivals is represented by a heavy red line next to the diagram, one centimeter representing 100 millival. The depth at which the groundwater sample has been taken is indicated below the diagram.

(*) By: Dr. J. I. S. ZONNEVELD, Geological Foundation, Section Geological Survey, Haarlem, Netherlands and Ir. J. H. BELTMAN, Government Institute for Drinkingwater Supply, The Hague, Netherlands.

Though this chart gives a good picture of the chemical composition of the groundwater, it does not show the relation thereof with the geology (lithology and stratigraphy). This relation is shown in the profile of plate 2.

Plate 2. Hydro-lithological profile of the province of Zeeland.

The following data are shown in this profile:

a. the chemical composition of the groundwater in the borings,
b. the lithology and stratigraphy,
c. the permeability of the layers.

To a. The chemical composition is represented in the same way as on the chart of plate 1, by coloured diagrams, below the respective borings. Moreover, the amount of each ion in p.p.m. (milligram per liter) and in millival per liter, is indicated on either side of the diagram.

The pH, the iron content (in milligram per liter) and the hardness (in German degrees) are indicated above the diagram, the depth at which the groundwater sample was taken and the year of the analyses below the diagram.

To b. The lithology is given in black symbols. The names of the stratigraphical units are written in the profile.

To c. The permeability — k — of the different layers (which has been computed from grain size analyses of the sediments) is indicated by colours, viz.:

$k = 0$ — 3 meters/day	white
$k = 3$ — 15 meters/day	yellow
$k = 15$ — 30 meters/day	green
k $>$ 30 meters/day	blue

In total 15 profiles, as shown in this example, have been made for the province of Zeeland, viz. 7 in a west — east direction and 8 in a southwest — northeast direction. Together these profiles give a comprehensive picture of the geo-hydrology of this area. It would be impossible to show the same data on one map only.

Plate 3. Geo-hydrological profile of the coastal plain of Suriname.

If the chemical composition of the groundwater is to be indicated in the profile itself, a seperate profile is needed for each compound.

The example shows the chlorine-content of the groundwater in a profile through the coastal plain of Suriname. The following graduations have been chosen:

0 — 100 p.p.m.	red
100 — 500 p.p.m.	yellow
500 — 1000 p.p.m.	green
$>$ 1000 p.p.m.	blue.

Plate 4. Geo-hydrological profiles of the Netherlands. Schouwen — Twente

Plate 5. and Goeree — Twente.

Plates 4 and 5 both show west — east profiles through the Netherlands, which give a generalized idea of the geology (lithology and stratigraphy).

The lithology — in black symbols — is shown only in the sections (columns) representing the borings through which the profile has been drawn.

The stratigraphycal units in profile 4 are shown in colours. Each stratigraphical unit includes of course layers of different lithological composition. A general idea of the lighology, for example the occurrence and extension of claylayers and aquifers, can be obtained from the sections (columns) representing the boings. In both profiles the chemical composition of the groundwater is represented in the same way as in the profile of Zeeland, viz, with coloured diagrams below the profile. The

depths at which the groundwater samples have been taken are indicated next to the sections of the borings in the profile.

In the profile of plate 4 the chlorine boundary of 100 p.p.m.(= 3 millival per liter) is indicated by a coloured line. In the profile of plate 5 the groundwater with a chlorine content of 100 p.p.m. and less is shown with a red colour, the groundwater with a chlorine content > 100 p.p.m. in green.

Plate 6. Aquifers in the eastern part of the province of Noordbarbant.

In many cases it is useful to know the depth and the thickness of the water-bearing strata. These data can either be represented by contourlines with reference to Ordnance Datum or by lines of equal depth below the surface.

The last method has the advantage that the map shows at once the depth to which drilling should be continued to utilize the waterbearing strata to their full extent.

Plate 6 gives an example of such a map. It shows the lines of equal depth below the surface of the top and the base of the coarse sand formations (Series of Sterksel, Zone of Veghel and Zone of Kreftenheye) in the eastern part of the province of Noordbrabant. The schematic cross-section shows that the geological sequence of the layers is rather simple. For the main part of the area the Zone of Veghel lies immediately on top of the Series of Veghel. Therefore the contourlines of the base of the Zone of Veghel coïncide with those of the top of the Series of Sterksel, which simplifies the picture. Nevertheless the map, though still legible, is already rather complicated. It does not seem practical to enter more data (e.g. hydrological data) on this map.

Plate 7. The boundary between fresh and salt water in the subsurface fo the province of Zuidholland.

Plate 7 shows the contourlines of a hydrochemical boundary surface, viz.) that of 300 p.p.m. chlorine, in the subsurface of the province of Zuidholland.

The map shows very clearly the occurrence of fresh water (red colour) in the dunes along the coast of the North See and in the sand body of the river «Oude Rijn».

Plate 8. Distribution of fresh and salt water at a depth of 50 meters below Ordnance Datum in the province of Friesland.

Boundary surfaces can also be represented by their intersection with horizontal planes.

Plate 8 shows the distribution of the chlorine content of the groundwater in a plane at 50 meters below Ordnance Datum, in thre province of Friesland.

The following chlorine contents have been distinguished:

0 — 100 p.p.m.	yellow
100 — 1.000 p.p.m.	green
1.000 — 10.000 p.p.m.	red
> 10.000 p.p.m.	blue

Also the boundary of the marine clay at the surface is indicated, showing the extension of the transgression(s) which caused the increased salinity of the originally fresh water.

Conclusions.

The examples shown on plates 1 — 8 give only some of the possibilities in which geo-hydrological data can be represented on maps and in profiles.

It will be evident from these examples that only geo-hydrological data of one or a few different kinds can be represented on one map or in one profile if a legible picture is to be obtained. For a certain area a combination of maps and profiles will be necessary to show the complete geo-hydrological sequence.

Different areas will need different combinations of maps and profiles, in accordance with the available data and the special use for which the maps and profiles are intended.

Furthermore a distinction should be made between maps and profiles for internal use of a service or institute and those for general use or publication. This distinction is based on practical grounds. Profiles, as shown on plates 4 and 5 are difficult to reproduce in printing, especially if a large series of such profiles is to be made. Profiles of this kind are visual documentations, for internal use only.

Profiles as shown on plate 2 can be reproduced in printing as in fact they are, together with geological maps and profiles and a description.

It depends on the number of available data whether much interpolation will be necessary. However, care should be taken to show in how far the representation of the data is based on facts and on interpolation. The reliability of the maps and profiles depends on this distinction.

LA CARTE HYDROGEOLOGIQUE DE LA REGION DE CASABLANCA

LUCIEN MONITION
Centre des études hydrogéologiques du Maroc

La carte hydrogéologique des environs de Casablanca établie par MM. L. Monition et M. Nerat de Lesguise fait partie d'un ensemble d'études géologiques et géotechniques entreprises dans cette région industrielle et agricole à forte densité de population.

Cette carte à l'échelle du 1/50.000, fondée sur l'observation de 800 points d'eau, couvre une surface de 750 km² environ. Elle montre le mode de circulation de la nappe aquifère dans des formations allant du Primaire schisteux et quarziteux au Quaternaire gréseux. Elle traduit l'effet désastreux des pompages intensifs dans la région côtière qui ont détruit l'équilibre nappe marine salée-nappe phréatique douce.

D'autres documents hydrogéologiques viennent à l'appui de cette carte :

—carte de la nappe phréatique au 1/20.000 limitée au périmètre urbain de Casablanca permettant de résoudre d'une manière plus efficace les problèmes de fondations.

—carte des salures. (résidus secs et chlorures) etc...

Toutes ces cartes ont été conçues dans un but éminément pratique et sont destinées à un large public comprenant entre autres, des agriculteurs, des colons, des entrepreneurs.

THE HYDROGEOLOGICAL MAP OF THE DISTRICT OF CASABLANCA

The hydrogeological map of the district of Casablanca which was drawn up by L. Monition and † M. Nerat de Lesguise is a part of a review of geological and geotechnical investigations in this densly populated industrial and agricultural district.

It is drawn to the scale of 1/50.000 after plotting 800 water levels and covers area of about 750 km² (sq. km). It shows how the watertable circulates in geological formations varyng from primary shales and quartzites to the quaternary sandstones. It reveals the disastrous effects of intensive pumping on the coastal border which distroyed the equilibrium between the phreatic fresh water and the salt waters of the sea.

Several other hydrogeological documents support the map

— a map of the phreatic waters at the scale of 1/20.000 limited to the urban perimeter of Casablanca permitting to solve in a very effective way foundation problems.

— a map of the salinities observed (% of salt per liter and chlorines) etc...

All these maps were meant to serve a most pratical purpose and at a large public composed of agriculturists, colonists and contractors.

Cette communication a été présentée au XX^{e} Congrès Géologique International de Mexico (Septembre 1956) et publiée dans les actes du Congrès dans la section 4 : « Géo-hydrologie des régions arides et subarides ». On se reportera à cet ouvrage pour le texte complet de l'étude.

GROUNDWATER MAPS FOR GENERAL DISTRIBUTION IN ILLINOIS

ROBERT E. BERGSTROM & LIDIA F. SELKREGG
Illinois State Geological Survey, Urbana, Illinois

Abstract

Recent increased demand for information about groundwater resources in Illinois established a need for rapid publication of reports describing geologic conditions and availability of groundwater for large blocks of counties, based on data at hand. Presentation of this information as regional circulars directed at municipal, agricultural, industrial, and legislative groups required preparation of maps showing distribution of aquifers with qualitative evaluations of potential water supplies.

For each circular, separate maps evaluate the occurrence of groundwater in the glacial drift and in the bedrock. Classification of groundwater potentialities from the drift is based primarily on geologic conditions but is guided by available production data. Maps illustrating groundwater conditions in the bedrock show the type and water-yielding character of formations directly below the drift and occurrence of the main aquifers at depth.

The over-all review of available data on groundwater in Illinois has provided new understanding of some areas of the State and has revealed deficiencies in basic data from other areas. In addition, the base data maps have expedited the handling of requests for information and service, guided the planning of detailed studies, and facilitated the preparation of other groundwater maps of Illinois.

Introduction

The severe drought that began in 1952 caused a great increase in demand for information on groundwater, addressed to the two State agencies responsible for studies of groundwater resources in Illinois. The demand came first from farmers after widespread failure of dug wells and small ponds. Somewhat later a number of municipalities that obtained water from reservoirs, small streams, or shallow wells experienced water shortages and asked for assistance in locating areas where suitable groundwater supplies might be obtained. As the drought continued, agricultural, industrial, and legislative groups sought information on the broad aspects of water and a delineation of favorable and unfavorable areas for procuring water in Illinois.

At the Illinois State Geological Survey, which is charged with study of the geological aspects of groundwater resources, a series of regional circulars describing the groundwater geology of large blocks of counties was begun, based on data at hand. These reports were planned for farmers, county agents, drilling contractors, legislators, municipal officers, industrial planners, and consulting engineers, and were printed by the planograph process. The reports were intended to provide general information on groundwater and its regional availability, and to serve as a basis for planning new groundwater developments. As completed, the series of reports consists of seven regional circulars which cover the State.

This paper describes how we prepared, for non-professional use, maps on groundwater geology and availability for large areas in a relativly short time, a program on which other State or governmental agencies similar to the Illinois State Geological Survey may embark in this age of growing public concern for water resources.

Geology of Illinois

Groundwater investigations in Illinois require the study of glacial-drift and bedrock aquifers. Most of the State is covered by glacial deposits which range in thickness from a few feet to more than 600 feet. The thicker and more gravelly deposits occur generally within the Wisconsin drift border in the northeastern quarter of the State. In the area of Illinoian drift in western and southern Illinois the deposits are generally thinner and, from the standpoint of water supply, less productive. Glacial valley-train sands and gravels occur along most of the main stream valleys and also in many important bedrock valleys that are now completely drift-filled.

Important water-yielding lower Paleozoic formations occur just below the drift or within favorable drilling depth in the northern third of Illinois, along the western edge, and across the southern tip. The central, eastern, and southern part of the State, within the Illinois Basin, has a thick section of Pennsylvanian rocks, mainly shale, just beneath the drift, and is therefore a rather unfavorable area in which to obtain water from the bedrock.

Sources of data

Preparation of the groundwater maps for the circulars was facilitated by abundant basic data and reports on file at the Illinois State Geological Survey. These and other sources of information include the following:

1) 145,000 records of oil and water wells and test borings, including 28,000 sets of drill cuttings, most of which have been studied and correlated; driller's logs; and 45,000 electric logs. These are filed by county, section, township, and range and are quickly available for subsurface studies.

2) Published and unpublished geologic investigations, including:

a. Quadrangle reports in about 80 out of a total of 288 quadrangles.

b. Regional stratigraphic studies of the glacial deposits and of many of the bedrock units.

c. Report and map of the bedrock surface of the State.

d. Detailed and regional reports on groundwater geology.

e. County road materials surveys.

3) State geologic map and topographic maps of 95 percent of the quadrangles in the State.

4) Maps and reports of about 500 electrical earth-resistivity surveys conducted in Illinois since 1932.

5) Records on well yields, water quality, and hydrologic characteristics of aquifers from published reports and files of the Illinois State Water Survey.

6) Water well contractors in the State.

Preparation of maps

The distribution of aquifers in Illinois is such that three types of maps were necessary to present the groundwater geology in the circulars: 1) A map showing the probability of occurrence and nature of sand and gravel aquifers, needed because the widespread drift has important but variable groundwater potential; 2) a map showing the distribution, nature, and water-yielding character of the shallow bedrock formations; 3) a map showing the depth or structure of the highly productive deep Cambrian and Ordovician sandstone aquifers in the northern third of the State. The maps were designed to be intelligible to non-technical readers.

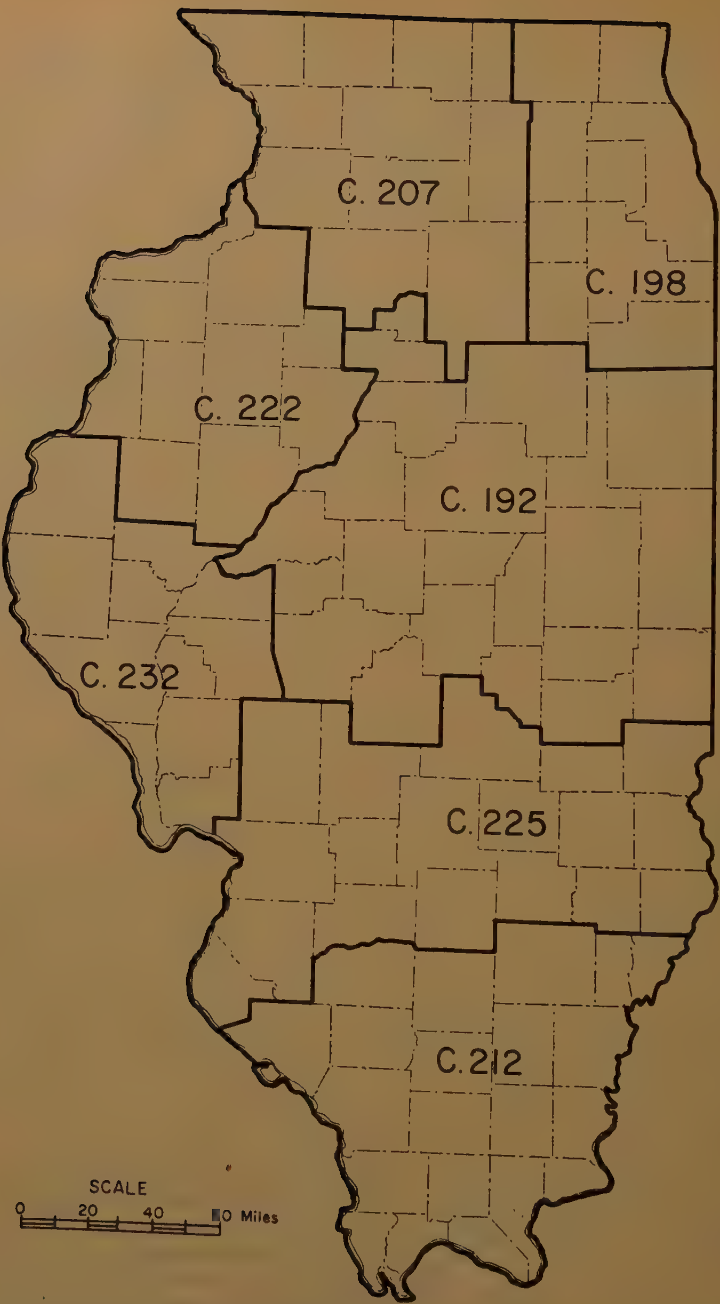


Fig. 1 — Map of Illinois showing regions for which Illinois State Geological Survey Circulars on groundwater geology have been issued.

The State was subdivided into regions on the basis of existing Agricultural Extension Districts, but boundaries were modified to avoid large generalized maps of undesirable proportions *(fig. 1)*. The smallest region covered is densely-populated northeastern Illinois (nine counties with a total area of 5,000 square miles) and the largest region is east-central Illinois (22 counties with a total area of 13,850 square miles).

Plotting of data

Data for most of the circulars were plotted on maps of scale 4 miles to the inch, but for northeastern Illinois, where there are a great number of water wells in the suburban areas around Chicago, on maps of scale 1 mile to the inch.

From the well records the following items were plotted where available: thickness of glacial drift, depths and thicknesses of sand and gravel, source of water, total depth of well, summary logs of formations penetrated, water yield, static level, specific capacity of the well, and notes on water quality. Most of the records are driller's logs and few of them contain more than three or four of the above items.

Most of the records are geologic in nature. Emphasis in plotting was on the occurrence and distribution of water-yielding or potentially water-yielding earth materials, although hydrologic data were plotted wherever obtainable. In areas where space did not permit plotting of all the well information, summary notations on general source and availability of groundwater were put on the map. The thousands of oil well driller's logs which were scanned in the course of plotting contributed little to our information on aquifers in the drift or shallow Pennsylvanian bedrock. However, electric logs of wells in the oil fields were examined in order to map areas where there are shallow Pennsylvanian sandstones that might produce small amounts of potable water for farm or domestic wells. Logs of coal tests have information on the lithology of the drift and bedrock but rarely contain notes on water-yielding zones. Driller's logs of water wells, checked against sample-study logs by Survey staff members, formed the basis for much of the later groundwater evaluation.

While plotting and evaluating the geologic information in terms of groundwater availability, reports of areal and stratigraphic geology and mineral resources were examined to aid in the interpretation of well records and to supplement the plotted information. Of particular help were maps of the bedrock surface; maps showing moraines and other glacial deposits; bedrock geology; structure, thickness, and facies of certain bedrock formations; and county sand-and-gravel surveys. Pertinent features such as buried valleys, outwash flats or terraces, glacial lake bottoms, areas of bedrock outcrop and thin drift, shallow oil or gas fields, and unusually favorable or unfavorable bedrock lithologies, were plotted or noted on the maps.

Maps Showing Groundwater Conditions in the Drift

The processes of plotting data and interpreting them on preliminary maps more or less overlapped. For the map evaluating groundwater conditions in the drift, the very favorable and the unfavorable areas, appearing essentially as alluviated valleys and bedrock outcrops respectively, were already rather well delineated. An intermediate area was added, so that the drift was subdivided into three areas of different groundwater potential. The areas were defined on the probability of occurrence and nature of sand and gravel aquifers, which are geologic characteristics, rather than upon hydrologic data such as well yields or transmissibilities. Well production data were used wherever available in evaluating the relative groundwater

potential between different areas, but boundaries were drawn on geological considerations alone in many places where no hydrologic data were available. A sand and gravel map for one of the circulars (Ill. Geol. Surv. Cir. 222, 1957) is shown in *figure 2*, and a composite map for the State, prepared by combining the maps in the circulars, in *figure 3*.

Fig. 2 — Probability of occurrence and nature of sand and gravel aquifers in western Illinois, north part (Ill. Geol. Surv. Circ. 222).

In the area most favorable for groundwater in the drift, the probability of encountering sand and gravel aquifers is «good to excellent.» Moreover, the aquifers are commonly extensive, thick, and highly permeable. From the standpoint of geologic characteristics the area is mainly the alluviated bedrock valleys which have streams

Fig. 3 — Probability of occurrence and nature of sand and gravel aquifers in Illinois.

or are completely drift-filled. A few small outwash plains are also included in this area. With respect to the bedrock valleys the boundaries of the excellent areas along present streams were generally easily delineated because the river bluffs and the edge of the valleys coincide and are commonly marked by bedrock outcrops. In buried bedrock valleys the boundaries were commonly drawn along a bedrock surface contour which corresponds to the elevation of the top of the coarse, permeable deposits shown in well samples or logs.

Well yields in the ranges of hundreds to thousands of gallons per minute are widely recorded in the most favorable area, though we do not imply that satisfactory high capacity wells are guaranteed at every site. Absence of high-capacity wells in some parts of the area where geological conditions appear to be highly favorable is not considered justification to grade these parts down to a lower category. The area labeled «good to excellent» is the logical area to explore for industrial, irrigation, and municipal groundwater supplies.

Much of the area classified as «poor» on the sand and gravel map appears on the bedrock surface map of the State as tracts of extensive bedrock outcrops. In detail it includes the followings: 1) driftless areas, 2) bedrock upland covered by a patchy mantle of thin drift (usually less than 30 feet thick), with bedrock cropping out along many of the creek cutbanks and road cuts, 3) well dissected uplands bordering parts of the Mississippi and Illinois Rivers, mantled by locally thick drift and loess, 4) valleys cut in bedrock and floored by thin alluvium, and 5) miscellaneous areas where well records and electrical earth-resistivity surveys indicate general absence of sand and gravel deposits. In general in this area, drilled wells must be finished in the bedrock even where wells of only a gallon or two a minute or less are required.

It was difficult to place a boundary between the «poor» and «fair to good» areas where thin upland drift grades laterally into thicker drift in morainic belts, in small shallow bedrock valleys, or along the flanks of major buried valleys. Generally well data are not adequate to draw this boundary with certainty. In some cases better definition was possible following field checks with drilling contractors. These were undertaken after preliminary maps were prepared.

In the area classed as «intermediate», the most extensive of the three, the probability of encountering sand and gravel aquifers is fair to good. Upland tracts with drift 40 or 50 feet or more thick, small stream flats, minor buried valleys, and the flanks of major buried valleys are included in the area. Thin, discontinuous to fairly extensive deposits of sand and gravel are known to occur or are indicated by electrical earth-resistivity surveys. These are quite commonly sources of groundwater for farm and other domestic wells. Locally, as in northeastern Illinois, well yields of several hundred gallons a minute are reported, but considerable testing is usually necessary to locate sites for wells larger than the average farm well. At some sites sand and gravel deposits suitable for drilled wells are absent, and wells must penetrate bedrock.

Maps Showing Groundwater Conditions in Bedrock

The bedrock maps embrace the three provinces into which the groundwater geology of the bedrock in Illinois can be conveniently subdivided:

1) Areas where pre-Pennsylvanian rocks are at the surface or underlie drift and yield potable water to depths of several thousand feet.

2) Areas where pre-Pennsylvanian rocks are overlain by Pennsylvanian rocks along the margin of the Illinois Basin and yield potable water from shallow to intermediate depths.

3) Areas in the Illinois Basin where thick Pennsylvanian rocks below the drift yield only small quantities of groundwater and where deeply-buried pre-Pennsylvanian rocks contain brine.

Portions of the maps in the pre-Pennsylvanian province show the simple distribution of lithologic-stratigraphic units, as modified from the State geologic map *(figs. 4 and 5)*. In the circular on northeastern Illinois we distinguished areas where

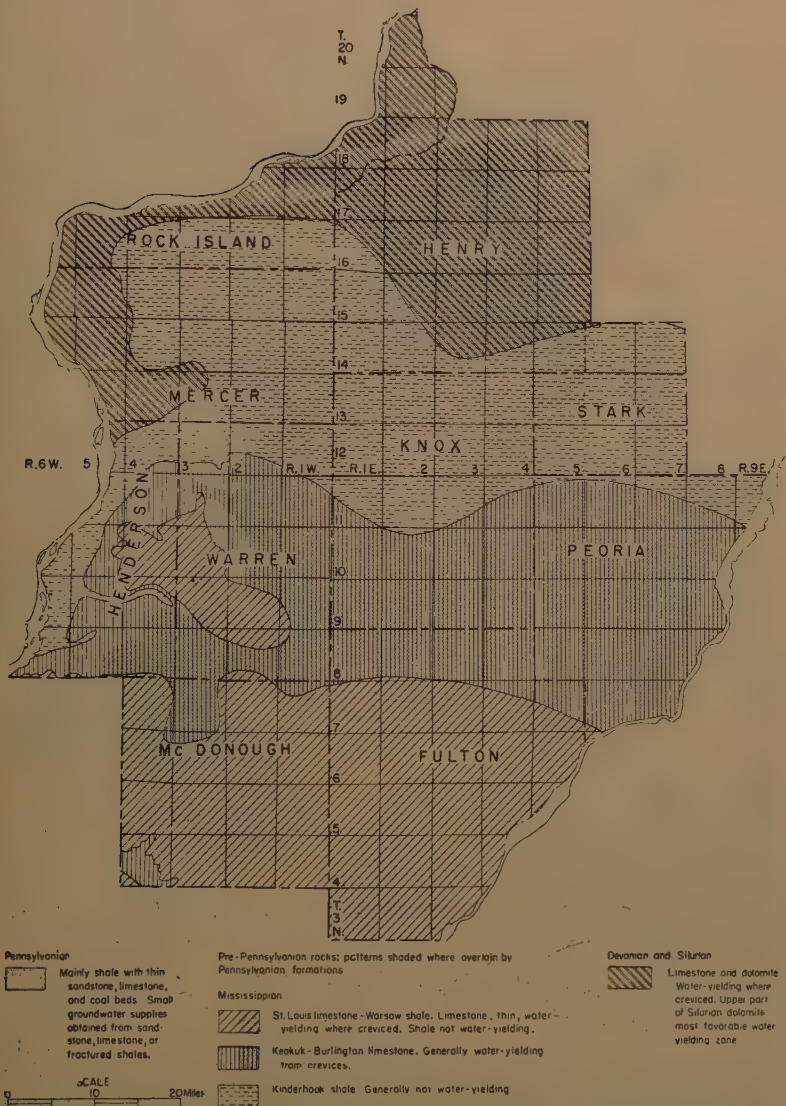


Fig. 4 — Areal distribution, type, and water-yielding character of upper bedrock formations in western Illinois, north part (Ill. Geol. Surv. Circ. 222).

Fig. 5 — Areal distribution, type, and water-yielding character of upper bedrock, including Tertiary-Cretaceous units, in southern Illinois, west part (Ill. Geol. Surv. Circ. 212).

the Silurian dolomite is known to be extremely well creviced and therefore unusually favorable for groundwater withdrawal and areas where it is consistently reported to be impermeable. We have since considered our mapping of groundwater conditions in the Silurian dolomite to be at best incomplete.

The pre-Pennsylvanian units are also shown within the Pennsylvanian border where they are sources of potable water. A pattern which does not obscure the patterns used for the underlying formations is used to show the extent of the Pennsylvanian rocks. Pre-Pennsylvanian units are not shown within the Pennsylvanian border in the deeper part of the Illinois Basin where they yield brine. Because sources of groundwater are scarce in much of the south part of the State where Pennsylvanian rocks are overlain by thin Illinoian drift, we delineated areas where Pennsylvanian sandstones which are likely to yield modest supplies of potable water occur within a few hundred feet of the surface *(fig. 5)*. Mapping of these shallow sandstones was done from study of oil well electric logs which are available in much of the area of thick Pennsylvanian rocks. Water quality was estimated from interpretation of resistivity logs (Pryor).

A third kind of map was included in the circulars covering northern Illinois to show the structure or depth of the important deep Cambrian (Galesville and Mt. Simon) and Ordovician (St. Peter) sandstone aquifers. In northeastern Illinois where surface relief is not great, depth to the top of the Galesville sandstone is shown by shaded patterns between contours. In northwestern Illinois where surface and structural relief are considerable it was necessary to use structure contours. Patterns are used to supplement contour lines on the structure map to clarify reading by the non-professional user.

After the priliminary maps were prepared for a region, we visited a representative number of the water well drillers in the area to compare our interpretation with their observations and to obtain specific information on drilling conditions. These visits commonly helped clear up uncertainties in transitional areas.

The maps were reduced photographically to a scale of about 15 miles to the inch for publication in the circulars. Summaries of lithology, water-yielding characteristics of the formations, and drilling and well construction details are given in an accompanying chart showing the rock column. The text of the circulars includes discussions of groundwater principles, regional geology, methods of developing groundwater supplies, and county groundwater summaries.

Conclusions

Preparation of the circulars provided an opportunity to experiment with methods of evaluating groundwater potentialities and presenting them on maps. Fundamental changes in the scope, method of analysis, and manner of presentation of groundwater information were made in the first three circulars before the method of study and format of the reports as here described were stabilized.

The first circular was primarily prepared for farmers and contains a single generalized map evaluating both drift and bedrock groundwater possibilities, based on the State bedrock surface map, spot checking of well records, and personal familiarity with the region by the authors. The other circulars were planned for all groundwater users and contain separate maps for drift and bedrock, based on systematic examination of all available well records and other geologic and hydrologic references.

Our maps evaluating groundwater potential in the glacial drift, on the basis of mainly geologic characteristics, received some criticism on the grounds that they are not based on quantitative hydrologic data. However, we believe the maps clearly outline the extremely promising areas as well as the extremely unfavorable areas

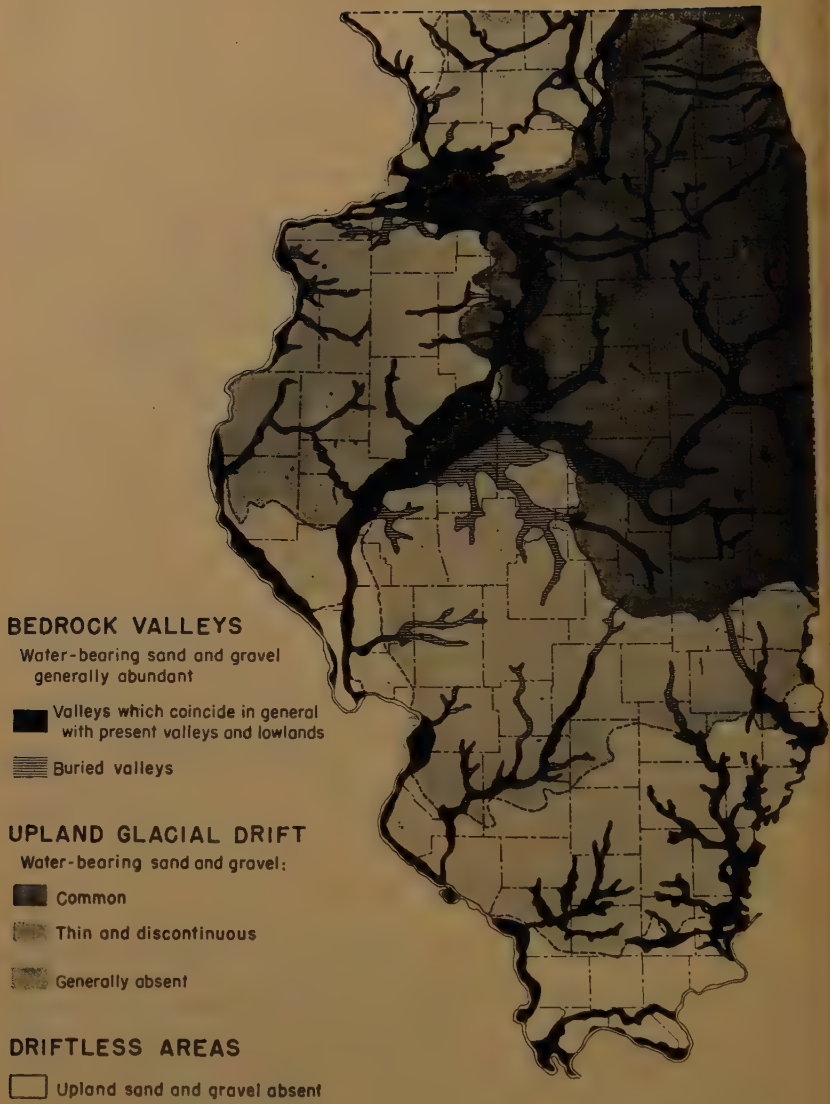


Fig. 6 — Occurrence of sand and gravel aquifers in Illinois, based on geologic data.

in the State and may therefore be useful in planning groundwater developments. Quantitative hydrologic data are of prime importance in assessing the groundwater potential in an area. However, in Illinois, as in most places, these data are not sufficiently abundant or properly distributed to permit delineation of reasonable

boundaries for any region of given groundwater potential. These boundaries must be drawn on the basis of geology and will include areas where quantitative information is lacking.

With regard to showing the water possibilities of the glacial drift of the State, our study indicated that a useful evaluation can be made on the basis of geologic information alone. Figure 6 is an early map which shows sand and gravel aquifers in the State, based mainly on the bedrock surface map, surface topography, and the distribution and lithology of drift sheets. It closely resembles the map prepared following systematic examination of all geologic and some hydrologic data during the course of the circular program (fig. 3). Differences are in details only, not in the broad picture.

We found that after the procedure was established in the first few reports subsequent circulars were prepared rather quickly. Local geologic or hydrologic problems or inconsistencies encountered during preparation of the circulars were noted for later consideration but, because they would not alter the broad picture dictated by the purpose of the reports and scale of final maps, were not pursued further during the circular program.

Several benefits to the Geological Survey and the State have resulted from the program of publishing regional circulars, in addition to providing groundwater information quickly for agricultural, municipal, industrial, and legislative groups. Review of the available data on groundwater in Illinois has provided new understanding in some areas and revealed deficiencies in basic data in others. In addition the maps on which data have been plotted have expedited handling of requests for information from the public, guided the planning of more intensive studies, and facilitated the preparation of other groundwater and geologic maps of Illinois.

REFERENCES

(1) Illinois State Geological Circulars 192, 198, 207, 212, 222, 225 and 232, 1954-1957.

(2) Pryor, W. A., Quality of groundwater estimated from electric resistivity logs, Ill. Geol. Surv. Circ. 215, 1956.

ÉTABLISSEMENT DES CARTES HYDROGEOLOGIQUES

J. MARGAT
Centre des Etudes Hydrogéologiques du Maroc

Résumé

Problèmes posés par l'établissement des cartes hydrogéologiques.
Choix de l'échelle, des éléments à représenter et des figurés en fonction des données locales, du but recherché et des utilisateurs prévus.
Propositions de signes conventionnels.
Les différents types de cartes hydrogéologiques.
Présentation comme exemple de la carte hydrogéologique d'une région subaride (Plaine du Tafilalet S. E. Marocain) au 1.50.000.

Introduction

La définition et l'établissement de cartes hydrogéologiques pose avant tout un problème de choix : choix de l'échelle, de la présentation matérielle de la carte, des figurés et enfin sélection des éléments à représenter. Il semble en effet impossible qu'un document puisse conserver un minimum de clarté si l'on y fait figurer la plupart des données géologiques et hydrologiques cartographiables.

Les critères en fonction desquels devront s'effectuer les choix, se ramènent surtout à trois : le but poursuivi, les conditions particulières de la région à cartographier, enfin les servitudes imposées par les nécessités de l'édition. De la variété de ces facteurs, résulte une assez grande diversité de types de cartes hydrogéologiques, qui correspondent beaucoup plus que les cartes géologiques à autant de cas particulier.

Il ne semble donc pas possible ni utile de concevoir des cartes hydrogéologiques régulières au même titre que les cartes géologiques et pouvant couvrir la totalité d'un pays.

Il n'est pas impossible par contre, et il est souhaitable que les essais tentés en divers pays soient accordés dans une certaine mesure et qu'un minimum de règles et de modes de représentation communs puisse être défini et recommandé.

I — Conditions d'établissement

Les objectifs assignés à une carte hydrogéologique sont surtout de trois sortes, qui correspondent à trois catégories d'utilisateurs :

But scientifique.

La carte hydrogéologique est le meilleur mode d'expression synthétique des connaissances hydrogéologiques sur une région donnée. En même temps qu'un but, elle est d'abord un outil de recherche. L'analyse, l'interprétation et la comparaison de cartes lithologique, piézométrique, thermique, géochimique, etc... constituent une méthode de travail indispensable et des plus fructueuses.

La publication de ces documents ne présente cependant qu'un intérêt de second plan, elle est rarement possible de manière complète et s'effectuera surtout dans le cadre des échanges scientifiques entre spécialistes.

But didactique.

La carte hydrogéologique est la base la plus commode et la meilleure illustration pour exposer et expliquer les conditions hydrogéologiques d'une région, à des fins d'enseignement ou pour d'autres buts. Sa clarté est dans ce cas, d'autant plus nécessaire, ce qui implique de restreindre au minimum les éléments à représenter. L'intérêt de la publication n'est fonction que du nombre des usagers éventuels.

But technique.

La carte hydrogéologique peut être enfin un document d'intérêt pratique directement utilisable par des usagers non spécialistes (Ingénieurs divers, Techniciens de travaux publics, de mines et d'agriculture, ou même Cultivateurs). Elle doit alors être de lecture facile et comporter exclusivement des indications directement utiles. Sa publication présente un intérêt général.

La cartographie de chaque région pose des problèmes spécifiques en fonction des conditions climatiques, hydrologiques et géologiques qui entraîne une complexité hydrogéologique plus ou moins grande : nombre de nappes superposées, fractionnement en unités indépendantes ou communicantes, variété de concentration des eaux, importance de l'exploitation des eaux souterraines.

Il est évident que l'existence d'une nappe (phréatique ou profonde) est une condition minimum pour qu'une carte hydrogéologique présente un intérêt. Sinon elle se réduit à une carte lithologique ou structurale agrémentée de quelques indications tectoniques et de points d'eau isolés. Une telle carte qui ajoute peu de chose à une carte géologique bien faite, ne mérite pas le nom de carte hydrogéologique. Quant aux cartes de points d'eau, elles sont essentiellement des documents d'archives, dont la publication ne s'impose pas.

Plus la complexité hydrogéologique est grande, plus il semble nécessaire de sélectionner parmi les faits à représenter, ceux qui sont essentiels.

Les nécessités imposées par les conditions de publication doivent enfin entrer aussi en ligne de compte. Le fond topographique pré-existant et le format voulu conditionnent souvent le choix de l'échelle. D'autre part, le choix des procédés graphiques et du nombre de couleurs dépend rarement de seules raisons techniques.

II — Elements a faire figurer sur une carte hydrogeologique

Ces éléments pourraient se répartir en deux classes : ceux dont la figuration doit être à peu près systématique et ceux dont la figuration sera surtout fonction des particularités locales et de la mesure dans laquelle ils ne risquent pas de nuire à la clarté de l'ensemble.

Parmi les premiers, on rangera les éléments géologiques et hydrographiques, les sources et autres points d'eau, la surface piézométrique de la nappe phréatique, l'extension de nappes profondes, les ouvrages hydrauliques. Parmi les seconds : la qualité chimique des eaux, la surface piézométrique de nappes profondes, les puissances aquifères, la topographie souterraine des murs ou toits imperméables, les coefficients de transmissivité et d'emmagazinement.

1. *Lithologie*

La représentation de la nature lithologique des terrains affleurants, doit surtout faire ressortir le degré et le type de perméabilité : on peut suggérer l'emploi de figures

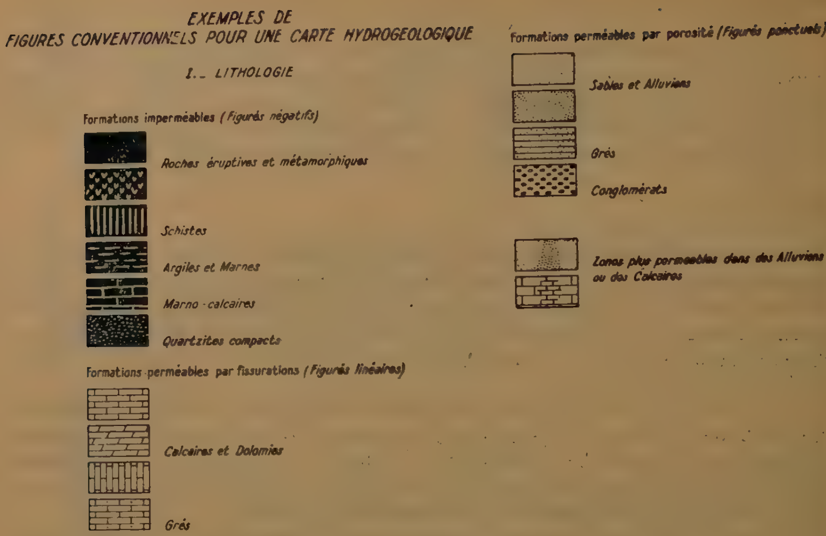


Fig. 1 — Lithologie

« négatifs » pour les terrains imperméables et « positifs » pour les terrains perméables (fig. 0), sans entrer dans les distinctions trop nuancées. Ce mode de représentation présente l'avantage de permettre de réduire le nombre de couleurs utilisées et d'alléger la carte plus que l'emploi de teintes unies nombreuses.

Les contours ne coïncideront pas nécessairement avec ceux de la carte géologique, la carte lithologique pouvant être plus détaillée que cette dernière ou au contraire ignorer certaines coupures stratigraphiques.

L'emploi de couleurs neutres et peu nombreuses parait préférable, les couleurs plus vives devant être réservées à des figures hydrologiques.

2. *Tectonique*

Le maximum d'indications tectoniques est à porter sur la carte, qui pourra être plus détaillée à ce point de vue que la carte géologique classique : pendages mesurés, axes anticlinaux et synclinaux, failles et contacts anormaux.

3. *Hydrographie et hydrologie superficielle*

On distinguera les cours pérennes des non pérennes, en indiquant pour les premiers le sens de variation du débit s'il y a lieu : ceci est surtout important dans les régions arides. La figuration des lignes de partage des eaux (limites de bassins versants et de sous-bassins), est également utile, de même que tous les plans d'eau naturels ou artificiels (lacs, étangs, marais, bassins de retenue).

Le figuré des points d'eau peut difficilement être complété systématiquement par la mention de renseignements ponctuels, tels que la température et le débit des sources, la profondeur de l'eau des puits, la qualité chimique de l'eau. Outre que la plupart de ces données varient dans le temps et qu'on devrait se borner à mentionner une valeur moyenne estimée plus ou moins arbitrairement, ces renseignements risquent de charger la carte à l'excès, surtout si les points d'eau sont nombreux.

Il en est de même de la mention de numéros de référence à un Inventaire qui ne paraît utile que pour des points d'eau importants (sources, forages, drains).

On peut suggérer que le nom des sources soit écrit en caractères proportionnels au débit, de la même façon que les noms de villes par rapport à la population, sur les cartes géographiques et qu'il soit souligné dans le cas de sources thermo-minérales.

Sources.

La figuration des sources pose un problème de classification. On ne peut entrer ici dans une étude critique complète des nombreuses classifications proposées et on se bornera à formuler quelques observations, en se limitant à l'objectif précis de la cartographie.

La classification de sources à adopter pour la représentation cartographique, doit semble-t-il répondre aux exigences suivantes :

comprendre un petit nombre de classes, reposer sur un critère unique et simple, rapidement et aisément déterminable sur le terrain, donner la prédominance à un critère hydrogéologique de préférence à tout autre (géologique pur, géographique, topographique, géochimique ou hydrauligque). Or la plupart des classifications proposées par divers auteurs (Gärtner, Meinzer, Kirk Bryan, Tolman, Blasquez) sont trop complexes pour constituer une base cartographique : ou bien les critères de base utilisés ne sont pas d'ordre hydrogéologique, ou bien aucune hiérarchie entre les multiples critères utilisés pour les divisions et les subdivisions n'est définie ni appliquée.

Le critère hydrogéologique de base doit être le rôle d'une variation de perméabilité de l'aquifère, c'est à dire l'absence ou la présence de l'imperméable et la position de ce dernier par rapport à la source.

On proposera donc, en s'inspirant surtout des classifications de Imbeaux et de Schoeller, les types de sources suivants :

a) *Emergence* : source résultant d'une intersection de la surface piézométrique d'une nappe avec la surface du sol, sans intervention visible d'un imperméable.

b) *Source de déversement* : source au contact — ou proche — du mur imperméable affleurant du niveau aquifère.

c) *Source de débordement* : source au contact — ou proche — du toit imperméable affleurant du niveau aquifère (en structure inclinée), ou d'un imperméable latéral.

d) *Source artésienne* : source provenant d'une nappe en charge, à travers un toit imperméable (généralement par faille).

On ajoutera deux cas particuliers d'émergence, courants dans les terrains calcaires:

e) *Exsurgence* : débouché d'un réseau aquifère en milieu fissuré

f) *Résurgence* : débouché d'une rivière souterraine provenant au moins en partie d'une perte d'un cours d'eau superficiel.

Des figurés simples pour ces 6 types de sources sont proposés ci-contre.

4. *Nappe phréatique*

Le figuré le plus important est celui de la surface piézométrique, représenté par courbes isopièzes ou équipotentielles (correspondant à un niveau d'étiage moyen de la nappe). L'équidistance des courbes est choisie en fonction du gradient de la nappe, de la densité des points d'eau (c'est à dire de la précision effective obtenue) et de l'échelle. La représentation des lignes perpendiculaires (filets d'eau) ne peut se substituer à celle des courbes isopièzes et ne paraît pas ajouter assez de précision pour figurer sur une carte publiée.

La représentation des profondeurs de la nappe par figuré de courbes isobathes peut être plus directement accessible pour l'utilisateur praticien, mais elle est surtout

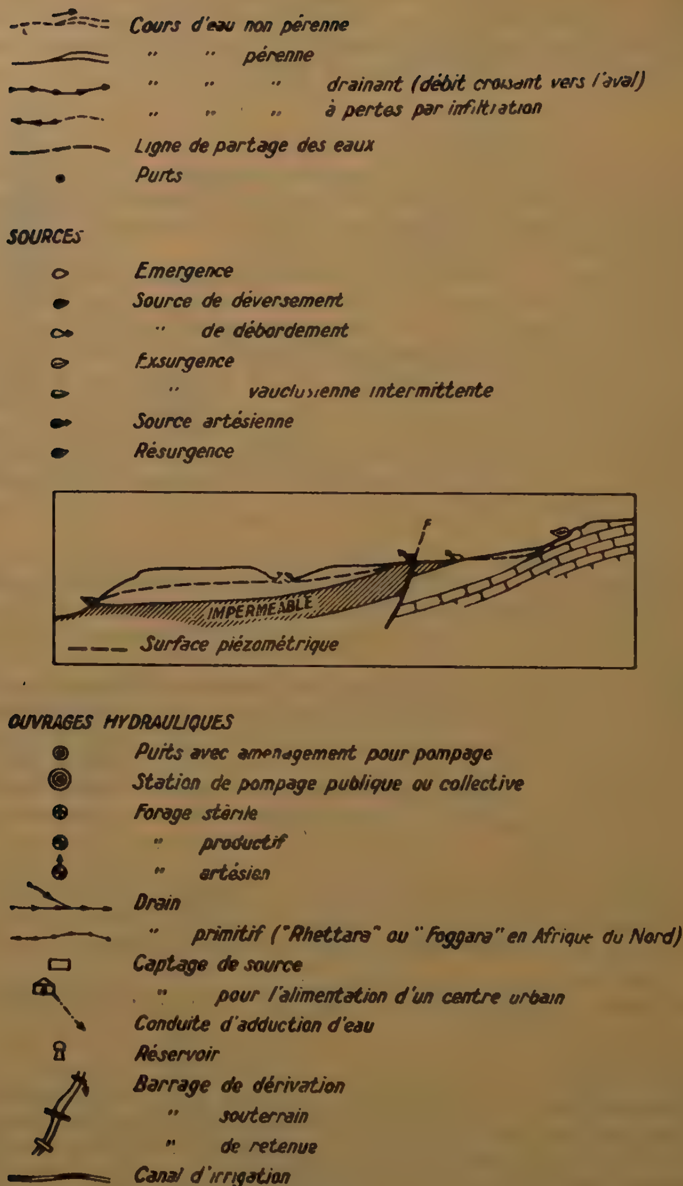


Fig. 2 — Hydrographie et hydrologie

significative dans une région très plane (plaine alluviale) où la surface piézométrique peut être plus accidentée que celle du sol. Elle paraît difficilement superposable à celle des courbes isopièzes sans nuire à la clarté et convient mieux à une carte annexe.

Il en est de même pour la représentation par courbes de la surface du mur imperméable et des puisances aquifères (courbes isopaques), lorsqu'elles sont assez connues.

Egalement intéressante peut être la représentation des variations de facies ou de nature lithologique de l'aquifère au niveau supérieure de la nappe : elle peut se concevoir par de simples changements de teinte des courbes isopièzes. L'arrêt du figuré de ces courbes peut enfin indiquer avec une précision suffisante les limites horizontales de la nappe. La représentation de la surface piézométrique par des courbes assez rapprochées rend inutile toute autre figuration de l'extension de la nappe par des rayures ou des couleurs unies.

5. *Nappes profondes*

La représentation de leur surface piézométrique, rarement connue avec autant de précision que celle d'une nappe phréatique, au moyen de courbes isopièzes, peut difficilement être superposée à celle de la nappe phréatique si elle existe, même en employant des couleurs différentes.

Il sera préférable de réserver des cartes annexes à cet effet et de ne représenter sur la carte principale que les limites d'extension connues ou supposées de ces nappes, ainsi que les points où leur existence est reconnue (sondages), avec mention de la profondeur du toit du niveau aquifère et de l'altitude de la surface piézométrique.

6. *Géochimie des eaux*

L'adjonction à la carte hydrogéologique d'indications géochimiques est beaucoup plus importante dans les régions arides et subarides, où les eaux sont très concentrées, que dans les régions humides. Le figuré de « courbes isocones » (concentration totale ou concentration de certains ions) est en régions arides d'une utilité pratique directe et il est souhaitable qu'il puisse être superposé à la carte de la surface piézométrique. Il peut se concevoir aussi par une gamme de teintes unies.

Des cartes plus particulières, comme celles de certains rapports d'ions caractéristiques, qui sont surtout des documents de travail, peuvent à la rigueur être annexées dans une notice.

7. *Hydraulique souterraine*

Il est rare que les caractéristiques hydrauliques des niveaux aquifères, (coefficients de perméabilité, de transmissivité et d'emmagazinement, débit spécifique) soient connus assez bien pour être cartographiables et en outre leur variation verticale, en général plus grande que leur variation horizontale soulèverait des difficultés. Si l'on dispose de données suffisantes, il sera possible d'exprimer les ordres de grandeur de ces caractéristiques par des figurés lithologiques plus ou moins denses par exemple, ou encore en utilisant une gamme de teinte pour chacun d'eux (fig. 1). Il convient de définir avec précision les caractéristiques représentées : trop souvent des cartes font mention de *débit* sans préciser s'il s'agit d'un débit spécifique exploitable par pompage, d'un module d'alimentation par unité de surface ou d'un débit moyen d'écoulement par unité de surface de front de nappe.

8. *Les ouvrages hydrauliques*

Il convient de figurer par des signes conventionnels d'une part tous les ouvrages hydrauliques de surface (barrages de retenue ou de dérivation, principaux canaux d'irrigation ou de navigation, digues, conduites d'adduction d'eau et réservoirs, conduites forcées), de même que les zones d'irrigation ou e'épandage et éventuellement les points d'injection où les bassins créés pour recharge de nappe; d'autre part tous les ouvrages d'exploitation d'eau souterraine ou de rabattement de nappe (captages de sources, drains, barrages souterrains, stations de pompage de toutes catégories, forages productifs ou stériles).

III — Choix de l'échelle

Il sera surtout fonction du but poursuivi, mais aussi de la complexité de la region cartographiée et du degré de précision des connaissances. Il peut aussi dépendre dans une certaine mesure des fonds topographiques existants.

Une carte à but surtout scientifique et technique ne peut guère dépasser l'échelle de 1/50.000. Au delà, il s'agira surtout d'une carte de synthèse (1/50.000 à 1/100.000). Enfin les échelles de l'ordre du 1/200.000 au 1/500.000, ne conviennent, comme les cartes géologiques de cette échelle, qu'à des cartes de reconnaissance ou synthèse très simplifiée pour l'exposition.

IV — Mode de publication

Le choix peut se présenter entre un calque hydrogéologique superposable à une carte géologique, pédologique ou simplement topographique et une carte hydrogéologique autonome.

La première solution présente des avantages certains pour certains types de cartes de petit format, réalisées dans un but principalement scientifique. On peut alors, par exemple dans un Atlas, répartir les éléments cartographiés sur plusieurs calques superposables, ensemble ou séparément à une carte géologique. Le principal avantage est la possibilité de réduire au minimum les figurés géologiques et topographiques et d'obtenir une carte peu chargée.

Les inconvénients sont cependant sérieux : il n'existe pas toujours une carte géologique publiée, à l'échelle choisie, couvrant la même région et suffisamment précise. Les coupures d'une carte hydrogéologique ne sont pas nécessairement celles de la carte géologique générale.

Enfin le maniement d'un calque est incommode dès qu'il dépasse un certain format.

Il semble donc préférable dans le cas général, que la carte hydrogéologique forme un document complet, ce qui ne saurait gêner sa confrontation avec la carte géologique.

Conclusions

En résumé, on peut concevoir l'établissement dans un pays donné, de trois types de cartes hydrogéologiques.

1. Des cartes régionales de chaque bassin ou sous-bassin sédimentaire constituant une « province hydrogéologique » homogène à des échelles de l'ordre du 1/20.000 au 1/50.000, pouvant se compléter lorsqu'elles couvrent des régions assez vastes

nécessitant plusieurs coupures, par une synthèse au 1/100.000 à 1/200.000. Les notices auront un caractère monographique et comporteront de nombreux documents annexes.

2. Des cartes techniques s'adressant à des usagers d'eau souterraine et couvrant seulement des régions où les problèmes sont assez importants et les usagers assez nombreux. Leur notice sera essentiellement pratique.

3. Une carte générale au 1/500.000 ou au 1/1.000.000 couvrant tout le pays, à but surtout didactique et pédagogique.

Présentation, comme exemple, de la carte Hydrogéologique du Tafilalt au 1/50.000

La plaine du Tafilalt, dans le Sud-Est pré-saharien du Maroc, présente des condititions très simples : c'est une plaine alluviale quaternaire comportant une nappe phréatique sur un substratum primaire toujours stérile. La forte concentration des eaux (de 1 à 25 g/l), effet du climat aride, a incité à compléter la carte de la surface piézométrique (en courbes isopièzes équidistantes de 1 m) par le figuré de la concentration (au moyen d'une gamme de teintes unies et de courbes isocones équidistantes de 1 g/l).

Une seule couleur, en divers figurés, a servi à représenter les affleurements du Primaire qui forment un encadrement complet de la plaine.

A l'échelle du 1/50.000 la carte forme une seule feuille de format 0,7 × 1 m. Il n'existe pas de carte géologique à la même échelle.

A GROUND-WATER MAP OF THE FEDERAL REPUBLIC OF GERMANY ON THE SCALE 1 : 1 000 000

RUDOLF GRAHMANN

RÉSUMÉ

La carte des eaux souterraines de la République Fédérale d'Allemagne 1 : 1 000 000 donne par des figurations différentes des espèces des roches aquifères. Ces figurations sont imprimées par couleurs différentes, qui en expriment la richesse d'eau en cinq degrés. Les couleurs pâles du fond signifient certaines qualités des eaux. Les eaux minérales se montrent par les symboles selon leur particularités. L'altitude de la nappe phréatique est donnée par les équidistances de cinq ou dix mètres. M. Wundt a essayé de déduire le débit de la nappe phréatique des débits minima des fleuves. On peut en déduire le débit des nappes en l/s/km². Les points de même valeur de ces débits sont réunis par des lignes vertes.

ZUSAMMENFASSUNG

Die Grundwasserkarte der Bundesrepublik Deutschland 1 : 1 000 000 gibt mit verschiedenen Signaturen die Arten der grundwassererfüllten Gesteine. Diese Symbole sind in fünf Farben gedruckt, die die gewinnbaren Wassermengen andeuten. Blaßfarbene Unterdrucke zeigen verschiedene Eigenschaften des Grundwassers an. Mineralwässer sind gemäß ihren wichtigsten Merkmalen mit verschiedenen Symbolen dargestellt. Die Höhe der Grundwasseroberfläche ist in Gleichen mit Fünf- oder Zehnmeterabstand aufgedruckt. Die von W. WUNDT errechneten Zwölftel der Summe der kleinsten mittleren Monatsabflußspenden vermitteln als Isolinien in l/s . km² Hinweise auf die dauernde Grundwasserbildung im Flachlande.

The quality of the ground water occurring in the pores and subsoil cavities of many rocks and obeying, in its movements, only the law of gravity is, in general, so favourable that it is particulary well suited for the water supply to population and industry. It is thus an asset which is all the more to be appreciated, the more good water is needed and the less water resources are available.

Like oil, ground water has the property of being permanently fluid with the temperatures prevailing in our climates. It can, therefore, move in the subsoil and accumulate in permeable rocks to such an extent that it can easily be withdrawn. To search for such waterbearing formations, is a task of hydro*geology* which may also be defined as the science of ground water resources or deposits.

Ground water holds a special position among all natural ground resources in that under appropriate climatic conditions it is continually replenished out of the percolating part of precipitations. It flows slowly on its way through the subsoil and finally comes to light as a spring or, more frequently, discharges into open waters, i.e. rivers, lakes or the sea. And thus it is integrated in the natural circuit of the water. This allows a permanent ground water withdrawal to the extent corresponding to its natural replenishment.

To ascertain the extent of ground water replenishment is the responsibility of the science of ground water economic, a branch of geo*hydrology* which also investigates the laws of ground water movement, particularly in the case of artificial withdrawals. If the pumpings exceed the extent of replenishment, an exhaustion of ground water resources takes place.

A *cartographic* representation of the ground water conditions must, on the one

hand. always be a hydro*geological* one. This means that it will have to show the occurrence and nature of water-bearing formations on the basis of the general geological structure. On the other hand, in our temperate climates, it will also have to take into account geo*hydrological* conditions, which means that it will have to contain data on the amount and nature of the *permanently* obtainable water. The map should show for every place the presence of ground water, the formation and depth in which it exists, its quantity and its nature.

In spite of the above mentioned general principles, the details of a ground-water map will yet be different as to contents and planning. In a *survey* of a larger territory, i.e. on a small-scale map, hydro*geological* data will play the more important roll, whereas problems of the ground water replenishment must play a lesser part, for the very reason that the results of research in this field are frequently still incomplete. Also for questions of water *quality*, a general map should only indicate some categories of substances, especially those, which make water unsuitable for the usual treatment, for instance salt (chlorides) or gypsum and so on. A small-scale general map will also indicate the regions suited for water supplies on a large scale, i.e. regions, where special geohydrological studies will have to be carried out. These are, in general, regions of waterbearing sands and gravels filled with water, where the formulas of Darcy and others can be applied. Largescale maps may represent not only the extension of the water-bearing formations, e.g. in several floors and with indications regarding their volumes, but also the values for ground water replenishment as depth (mm) or as yield ($1/s \cdot km^2$) as well as dissolved matters in the ground water.

After World War II, most of our cities were destroyed by airraids. In many cities, the number of ruined houses and dwellings amounted to 50 and even to 90 %. Also industrial plants were for the greater part destroyed. But these overground ruins visible to everybody were not the only damage. Also below ground, owing to bomb hits the pressure of which is propagated to far distances, great damages occurred on the invisible main systems in the subsoil of every town. Particularly sensitive were the water conduits, the piping system of which had been hit in numerous cases or had become leaky owing to a dislocation of the sockets. Thus in some cities, the resulting losses of pure water equalled nearly the percentage of destroyed dwellings. Accordingly, much more water had to be pumped than was consumed.

Within a short time, nine million people crowded into this area, who had been expelled from their homes which they had occupied since the Middle Age. Moreover, in spite of the dangers involved, nearly three million people, tired of authoritarian political systems, infiltrated in the course of few years from the Communist-ruled Eastern part of Germany into Western Germany whose population rapidly increased by 30%.

It will be easily understood that for all these reasons our water supply which is based up to 90% on ground-water was extremely strained. Requirements still increased very much when, after the introduction of a stable currency in June 1948, our economy showed a rapid and steep upward development which has continued until to-day. Though the Geological Surveys of the Länder which are preponderantly in charge of hydrogeological work were in a position to meet the demands made upon them, there were other sectors, e.g. those engaged in planning at long sight, where a survey of the general ground water conditions in the Federal area was still wanting.

It is for this reason that a *working group*, consisting mainly of state geologists, myself being the chairman of this group, prepared on my proposal and under the auspices of the Federal Ministry of Economics a general hydrogeological 500 000-scale map covering on 14 sheets the whole territory of our Republic. Each sheet is accompanied with an explanatory booklet of about 100 pages in which the hydrogeological bases of water supply are dealt with in detail. I reported on it briefly already

in my lecture delivered at our Rome meeting in 1954 (Publication No. 37 de l'Association Internationale d'Hydrologie. Assemblée Générale de Rome, tome 2).

In the meantime, thanks to the cooperation of more than 30 authors, all the 14 sheets of this map have been published. The explanations accompanying the maps have a volume of, altogether, more than 1500 pages with 132 illustrations, 16 diagrams, more than 200 tables, many schedules of geological layers and water analyses. For more than 4500 communities, the kind of water supply is described. It is thus possible now to get quick information of the ground water conditions of every part of our Republic.

Thereupon there appeared the need for a map representing the whole Federal area (250 000 km²) on *one* sheet. The 1 000 000-scale was chosen, particularly as many maps of the Federal area on this scale are already available. I am presenting to you this groundwater map, because it may well be the first of its kind which has been printed for a whole country. As is to be expected whith this scale, it is in the first place a hydro*geological* map. Accordingly, it contains indications about every point of the territory and not only about such zones as supply abundant groundwater and for this reason have in general been better explored.

Our map is showing in blue colour in several shades the zones of much and even abundant groundwater; whereas shades of red colour represent the territories with only few groundwaters. Of course it would be best, to represent by these colours or as isolines the amount of the permanent replenished groundwaters as height in mm or as yield in l/s . km². But this would be possible only for a few parts of our country. For this reason we must restrict ourselves to representing only the presumed water yields.

The latter are understood to be the amounts of water which in the case of a corresponding ground water replenishment can be permanently taken by an economically bearable waterwork. We are, however, aware of the fact that this definition of the presumed water yield is no *exact* scientific term, for, on the one hand, the economic feasibility depends both on the economic strenght of the water consumer and on the state of technics. It can thus vary, i.e. probably increase, according to technical efficiency, and this, of course, everywhere to the same extent. On the other hand, also things which are not entirely equal are compared, e. g. in the case of the output of a single well with a very great depth in a zone of low yield, against the output of a range of a hundred and more wells in river gravel of high ground water humidity. But just as on the one hand nobody will try to obtain water from rocks of low water bearing by a hundred borings at 100 m depth each, nobody will on the other hand content himself, in case of large demands, with only *one* well of 10 to 20 m depth in sand or gravel. Our definition of presumed water availabilities constitutes thus the application of *Adolph Thiem*'s specific yield, and our representation will in this way be best suited for practical purposes.

For this reasons we say in our legende:

In general, in case of sufficient groundwater replenishment, the following daily quantities (m³) can permanently be extracted from economically bearable tapping points:

10 000 violetblue,
1 000 coldblue,
500 greyblue,
$>$ 100 orangered,
$<$ 100 crimson.

For territories, where the yield is different at so short distances, that it cannot be shown on our smallscale map, we have introduced an alternation group in brown colour comprising all yields from

0 to 1000 m³ daily.

The different groups given in our map are the result of gathering all pumping tests available and of long years experiences of water works. In the booklets accompanying the fourteen sheets of our map 1 : 500 000 we have given many examples.

For many purposes it might be useful to know the kind of the waterbearing subsoil. On our map 1 : 500 000 we give this by different symbols, printed in grey colour. On the new map, lying before us, we represent the different kinds of aquiferous rocks in a similar manner, i.e. we give sand by points, gravels by rings, sandstones by parallel lines and points, clays by short strokes, lime stones by brickpattern and so on. In a similar manner we could represent the places where the sedimentary rocks lie horizontally or where they are folded, either in the palaeozoic (varistic) or in the cainozoic (alpine).

All these rock symbols are printed in the colours of their spécific water yield, i.e. in blue shades, if they contain much water and in red ones if they are poor on water. We think, that by this method our map is clearly legible.

The altitude of the ground water level could be represented for some particularly well explored regions. For the Munich plateau, watertable contours were indicated by isolines in distances of ten meters from 610 m above mean sea level down to 440 m above mean sea level. For the plain of the Upper Rhine, we show such contours from 260 m above mean sea level near Basle down to 85 m above mean sea level at the mouth of the Mainriver near Frankfurt, mostly in distances of 5 m, according to a study by W. WUNDT. Finally, the map contains such fivemeter contours also in the region of the Lower Rhine from 210 m above mean sea level south of Bonn down to 10 m above mean sea level near Kleve at the German-Dutch frontier, according to a study by the government of the Land North-Rhine-Westphalia.

By the representation of *deeper* water floors a hydrogeological map can be overcharged to such a degree that its legibility suffers. It must, therefore, be limited to special cases. In the first place, a deeper floor should be represented only if it contains good and usable cool water, and if the obtainable amount of it is not less than that of the upper floor. However, the cartographic representation may also be omitted if the occurrence of a deeper floor already follows from the well known geological stratigraphy. In our regions, this is for instance the case in the mesozoic beds deposited in mostly even layers with their changes of sandstones, clays and limestones. On the contrary, the occurrence of tertiary formations is, in general, rather irregular in Germany owing to their preponderantly terrestrial origin. As they frequently consist of sands and gravels which carry large quantities of mostly good ground water, often even artesian or subartesian, these deep ground waters which are important for the water supply have been specially indicated on our map by a pale grreen background shade, e.g. in Schleswig-Holstein and in Bavaria.

Our map shows likewise geological dislocations, frequently having a hydrogeological effect; springs with a minimum yield of more than 1 m^3/s, of course all in karstic areas. For the areas of palaeozoic (varistic) formations, mostly poor on groundwater the map shows all barrages with a useful space of more than 1 hm^3 serving to water supply.

The same kind of representation by pale background colours is employed to indicate some important qualitative properties of the ground waters,

in pale brown:

salty ground waters frequently occurring in many parts of Germany in several strata of the permian and of the mesozoic, especially in the northern Germany owing to the permian salt stocks and on the coast of the North Sea but occasionally also of the Baltic Sea;

in grey:

acid ground waters which, due to peat bogs, bear much humic acid and therefore have a particularly aggressive effect.

All other chemical properties, e.g. the contents of iron and manganese, vary too rapidly so that they cannot be indicated on a small-scale map.

However, we have classified the *mineral waters*, according to their most important properties, as follows:

Chloride waters and brines; sulphate waters, hydrogencarbonate waters; mineral springs charged with carbon dioxide and mofettes; contents of arsenic, iron, iodine, radium, sulphur; thermal springs.

Mineral springs charged with carbon dioxide, mofettes and thermal springs play an important role especially in the vulcanic formations of Rhineland and Hessen.

The very important ground water replenishment from the part of precipitations infiltrating into the ground can be ascertained by different methods which, however, are mostly applicable only in sand and gravel zones containing much ground water; and even then are always affected by uncertain factors.

For instance, an attempt can be made to compute the annual amount of ground water replenishment on the basis of the annual rise of well levels. But the drawback in this method is that also during the rise of the level a ground water run-off takes place which, of course, should cause a lowering of the level the extent of which can only be computed with difficulty. In any case, however, the rise of level in the well is smaller than that caused by the real increase in ground water would be, if the groundwater run-off were stopped. In order to convert the real ground water increase into terms of water level, it would be necessary to know the effective void space of the ground water bearing formation, which, however, seldom occurs. In general, 20% are expected in river gravels, but this is only an assumption. In the case of a real rise of the ground water by 0,50 to 1,00 m, it would correspond to a water level rise of 0,10 to 0,20 m.

Another method is to deduct from the precipitations the amount of evaporation which, though differing according to configuration of terrain, climate and vegetation, does not vary within such a wide range as, for instance, precipitations. For the territory of the Federal Republic of Germany an average depth of evaporation of 460 mm can be computed on the basis of the mean of the precipitations and run-offs of many years. Of course, it would be more appropriate to use the average value for a smaller area. It would thus be possible to compute the ground water amount on the basis of precipitation minus evaporation and to represent it in terms of water heights in mm or also in terms of yield in $l/s \cdot km^2$. Of course, also this method has many sources of error and is, in fact, only applicable in geologically uniform zones, i.e. in large sand and gravel areas.

By way of experiments, in imitation of natural conditions, attempts are being made to solve the problem by observations with *lysimeters* filled with different kinds of soil and subsoil. The values of the percolation amounts thus obtained may be very reliable and useful for uniform zones, e.g. dunes with little vegetation. In general, however, it seems that the values of percolation obtained in lysimeters are somewhat greater than the ground waters which finally discharge into open waters, for on their underground way, through the capillar fringes, they deliver a non-ascertainable amount of water to the vegetation.

Another method which takes into account also the natural conditions and which was early applied by ADOLPH THIEM and other practical geohydrologists, consists in computing the replenishment of groundwater on the basis of the relation between the quantity of permanent withdrawal by one or more wells and the area of the drawdown cone caused thereby. The principle underlying this method is straight forward and simple. The method has, moreover, the advantage that the many small differences existing as to the composition and structure of many groundwater bearing formations are balanced in favour of mean value. But, also this method has its difficulties and sources of error. In order to obtain exact results, the withdrawal

must be continued for a long time and, as far as possible, always to the same amount. Experience has shown that a drawdown cone will increase for very long times. And too it is not possible to determine its dimensions with certainty because towards its borders the rate of depression is so slight that it is difficult to distinguish it from the natural fluctuations of the ground water level. In any case, very exact work and great experience are required to define the limits of a drawdown cone correctly and to distinguish it precisely from the cone of depression (R. Grahmann, 1936).

Finally, E. Natermann has shown a method to compute the amount of the current ground water replenishment for a river system. Starting from the fact already known for some time that in dryweather periods open waters are fed exclusively by the discharge of ground water, he considers the dryweather runoff as measure for the inflow of ground water. If the low water levels of a yearly run-off line are connected, a tangent line lying against it is obtained which constitutes a measure of the ground water run-off during the year.

Since the lowwater levels indicated for all months in our hydrological yearbooks are averages of many years, it seemed that against these values a tangent line should be laid which would then be the average value of groundwater amounts for many years. Professor Walter Wundt was so kind as to compute, isolines of the twelfths of the smallest monthly average yields (l/s . km²) of open run-off. These contours have been printed on our map in green colour.

The study shows, that even this method is not applicable everywhere. For all territories with a high precipitation rate, especially in mountainous areas, it gives too high values which cannot be traced back to subsoil waters affluxes alone. This is probably due to the circumstance that the precipitations are not only higher but also more frequent. Therefore in territories with a high precipitation rate e.g. in mountains dryweather times and minimum runoffs do not accord with those observed in the plains with their lower and scarcer precipitations. Probably in mountains the forests with their dense underbrush and soil vegetation play a great role hindering and delaying the runoff by interception; so that dryweather times are to a certain degree bridged.

The open runoff isolines on our map refer therefore only in the plains to the groundwater runoff with little differences being possible. But even here they are to be used in a reasonable connection with the hydrogeological representation. This means for instance, that a lowest run-off of 5 l/s . km² in an area which consists half of sand and half of clay areas, may result *only* from the sand, so that its yield of groundwater should be assumed to be 10 l/s . km² the clay on the contrary yielding nothing. And so on.

The map will be accompanied by an explanatory booklet.

LITERATURE

Grahmann, Rudolf, Absenkungstrichter oder Entnahmetrichter ? Das Gas- und Wasserfach, 1946.

Grahmann, Rudolf, Die Aufnahme der Grundwässer im Lande Sachsen. Jahrb. Reichsamt f. Bodenforschung f. 1942/43. Berlin 1943.

Natermann, E., Die Linie des langfristigen Grundwassers und die Trockenwetterlinien. *Mitt. Bundesanstalt f. Gewässerkunde* Nr. 22, Bielefeld 1952; see also

Horst, Hans, Die Grundwasserspenden in Niedersachsen. Neues Archiv für Niedersachsen, Heft 26, Jahresband 1951.

Grahmann, Rudolf, Der Hydrogeologische Arbeitskreis beim Bundesministerium für Wirtschaft. *Ber. z. dt. Landeskunde*, Bd. 11, H. 1, 1952.

CARTES DE LA HONGRIE INDIQUANT LES QUALITES DES EAUX SOUTERRAINES

Mme L. SZEBELLEDY
Docteur ès sciences

Résumé

En vue de l'emploi des eaux souterraines dans l'industrie et l'agriculture, il importe de connaître leur composition chimique ou les qualités de certains éléments qui y entrent. Notre but est de fournir aux hommes du métier une vue d'ensemble facilement intelligible de la qualité des eaux souterraines de notre pays.

Nous avons trouvé que parmi tous les modes de représentation en usage c'est celui par courbes isométriques sur cartes hydrochimiques qui s'est avéré le plus adéquat.

Afin de pouvoir dessiner ces courbes nous avons réuni dans les divers instituts du pays s'occupant d'analyses d'eau les données relatives à la qualité des eaux d'environ 60.000 puits. Sur la base de celles-ci nous avons dressé trois cartes. La première renseigne au sujet des conditions de la concentration de la teneur en sulphates de l'eau, la seconde représente les variations de la dureté des eaux, tandis que la troisième indique les eaux classées en divers types suivant la prédominance des cations et anions.

En procédant à la cartographie nous préparons des croquis à l'échelle de 1 : 50,000 du territoire de tout le pays, croquis sur lesquels nous reportons les données réunies sur la base desquelles nous dessinons les courbes isométriques. Sur la base des feuilles à l'échelle de 1 : 50.000 on construira les trois cartes au 1 : 200,000 du pays.

Six croquis de cartes en annexe

Les annexes représentent les conditions de la teneur en sulphates, de la dureté et des types pour les régions du Pays à l'Ouest du Danube et à l'Est de la Tisza.

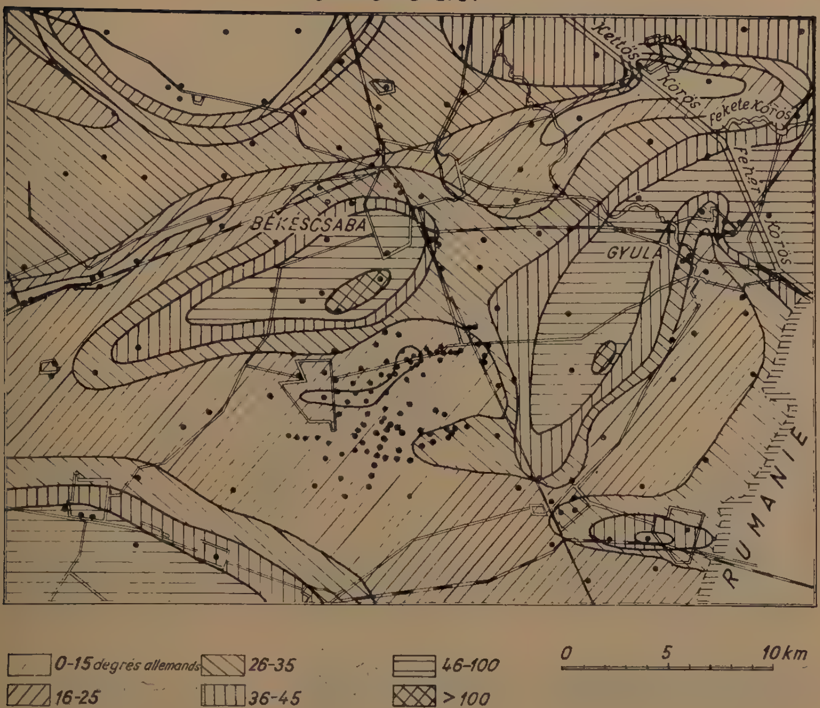
Il est inconcevable de nos jours de mettre à l'étude des projets d'établissements industriels et de distributions d'eau ou l'emploi de l'eau dans l'agriculture sans connaître la composition chimique de l'eau disponible à ces fins. L'agressivité de l'eau constituant un danger pour les éléments en béton et en métal des ouvrages d'art, sa dureté lorsqu'elle sert à alimenter des chaudières sont des facteurs que l'on ne peut négliger.

Dans les divers instituts du pays s'occupant d'analyses d'eaux nous avons pu trouver les données qualitatives des eaux de plus de 150.000 puits, sur cartes ou éparses dans des procès verbaux d'analyses d'eaux. Notre but était de rassembler ces données et de les représenter de façon à permettre aux hommes de métier travaillant dans l'industrie et l'agriculture de se faire rapidement une idée de la qualité de nos eaux souterraines.

Le premier pas était donc le rassemblement et le classement des données et parallèlement l'élimination du superflu. Ce sont les données de la nappe phréatique que nous avons étudiées par puits creusés et forés. Ayant éliminé le rebut nous avons conservé 60.000 données pour construire la carte du pays.

La seconde tâche était de trouver le mode de représentation le plus adéquat. Les modes employés le plus souvent en Hongrie, avec étoiles et secteurs, conviennent pour comparer les divers types d'eaux ou pour illustrer les conditions qualitatives des eaux de régions d'importance moindre. Mais ils ne peuvent pas servir pour représenter de façon synoptique l'élaboration basée sur 60.000 données. Il en est de même d'ailleurs pour tout mode de représentation où il faut indiquer les données de chaque puits séparément. Pour cette raison la représentation avec lignes isométriques sur cartes hydrochimiques a paru la plus adéquate.

1. La dureté totale.

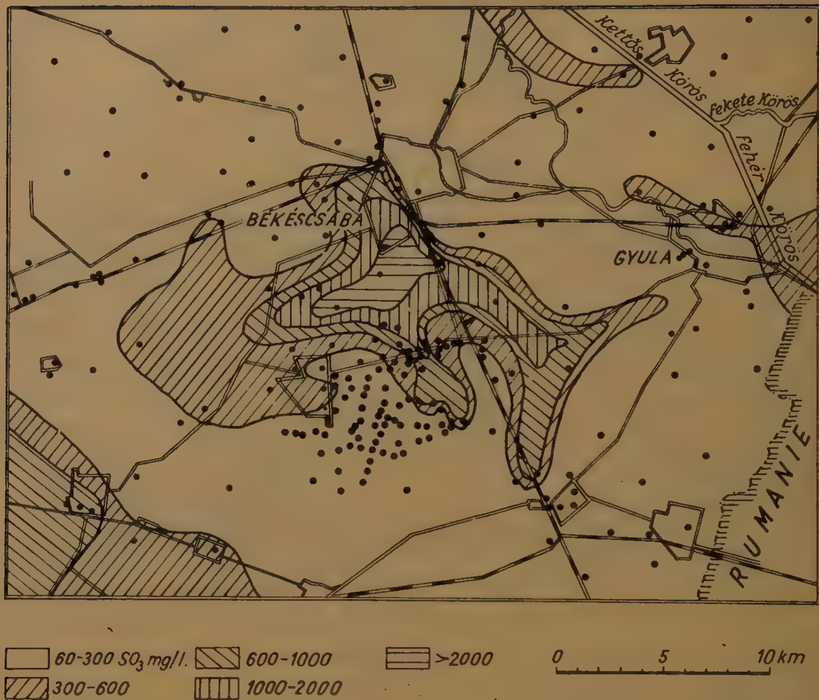


En élaborant des cartes représentant un seul composant nous n'aurions pas résolu le problème, nous en avons donc préparé trois. Au point de vue de la construction il importe de connaître la teneur en sulfates, l'une des cartes représente donc les conditions de la concentration de la teneur en sulfates des eaux. La seconde carte représente la variation de la dureté totale des eaux du point de vue de leur emploi dans la construction, de leur adoucissement en vue de servir dans des chaudières, enfin du point de vue de servir d'eau potable. La troisième carte indique les eaux classées en divers types suivant la prédominance des divers cations et anions. Elle rend de bons services dans les études au sujet du rapport entre la qualité du sol et celle des eaux souterraines, des variations de la qualité des eaux, du rapport entre les qualités des eaux superficielles et souterraines, de la qualté des eaux d'irrigations etc. En dehors de ces trois cartes on pourrait encore envisager d'en construire du point de vue de l'hygiene ou d'autres, mais nous avons remis leur préparation à une date ultérieure.

Au cours de la préparation des cartes nous avons d'abord dessiné des croquis a l'échelle de 1 : 50.000, sur lesquels nous avons marqué les emplacements des puits et les valeurs chimiques correspondantes, puis nous avons construit les courbes isométriques. Ensuite nous avons réduit ces croquis à l'échelle de 1 : 200.000.

Les trois croquis en annexe représentent les conditions de la teneur en sulfates, de la dureté et des types d'eaux d'une seule et même région de la Hongrie à l'est de la Tisza. Considérant tout le pays d'intéressantes variations qualitatives peuvent être observées sur la base de la carte, en confrontant p. ex. les eaux à très faible

2. Le contenu en sulfates.



teneur en sulfates de la Transdanubie à celles de régions à l'Est de la Tisza — voir annexe 2 — qui en contiennent beaucoup, par ailleurs en considérant des écarts dans les types qui ne ressortent évidemment pas des croquis annexés.

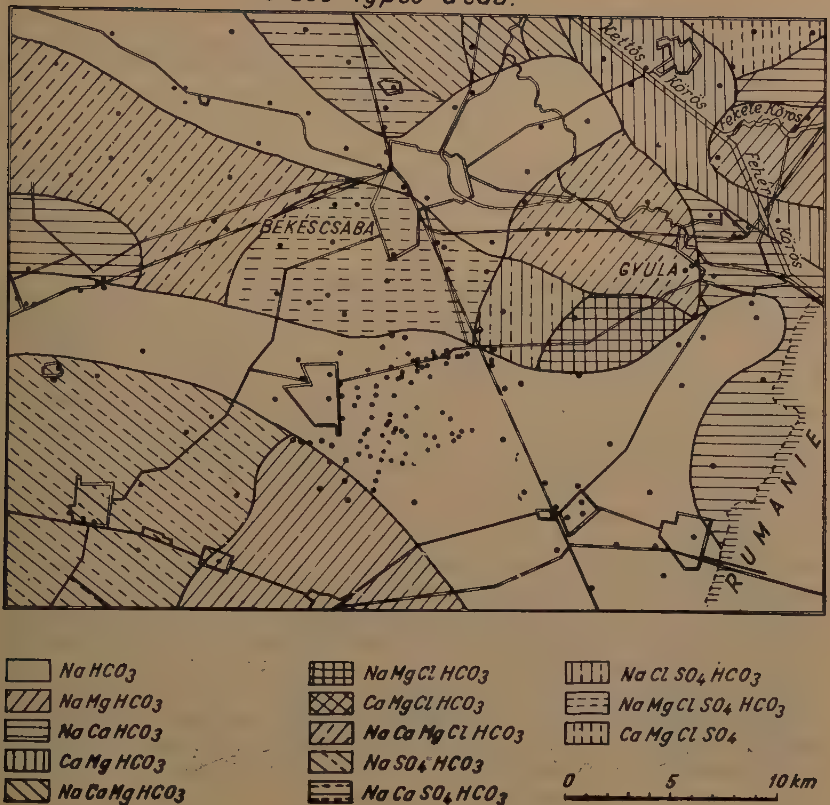
Le croquis no. 1 représente les variations de la dureté totale. Les régions contenant de l'eau d'une dureté de 0-15, de 15-25, de 25-35, de 35-100 et de plus de 100 degrés allemands ont été délimitées entre elles par des courbes continues correspondant à 15, 25, 35, et 100 degrés de dureté.

Le croquis no. 2 représente, suivant le même principe, la teneur en sulfates. En choisissant les valeurs-limites nous avons tenu compte des normes en vigueur dans la construction. Les régions délimitées par les courbes isométriques sont celles dont les eaux contiennent 0-60, 60-300, 300-600, 600-1000 et 1000-2000 mg/l de sulfates exprimés en SO_3.

En représentant les types d'eau sur *le croquis no 3* nous avons classé ceux-ci suivant leur teneur en cations et anions. Ce classement est basé sur la prédominance relative des 3 cations ($Na^{\cdot}$, $Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$,) et des quatre anions (Cl', SO_4'', HCO_3', CO_3'') qui se rencontrent le plus souvent. Les résultatss de l'analyse sont exprimés en pourcent d'équivalence et chacun des types comprend des eaux dans lesquelles celui de certains cations et anions dépasse les 25 %, en comptant séparément l'équivalence des cations et celle des anions.

Considérant ce qui précède l'eau se dit contenir du sodium, de la magnésie ou du calcium si un seul cation est prédominant. S'il y en a deux qui prédominent on parle d'eaux à sodium-magnésie, à sodium-calcium ou à magnésie-calcium, enfin

3. Les types d'eau.



s'il y a trois cations on désigne l'eau comme contenant du sodium, de la magnésie et du calcium. Les mêmes variantes se rencontrent au cas des anions aussi, où l'on parle suivant la variation en ordre de grandeur des divers anions d'eaux sulfatées, carbonatées, sulfatées-bicarbonatées, chlorurées-sulfatées, etc.

En se servant des cartes on doit se rendre compte qu'elles ne peuvent fournir que des renseignements d'orientation, qu'elles montrent donc seulement quelle sera en ordre de grandeur la dureté totale et la teneur en sulfates de la majeure partie des eaux dans la région en question et à quelle eau l'on peut s'attendre au cas où on ferait un nouveau forage. On voit p. ex. sur le croquis en annexe que dans les environs de Békéscsaba l'eau a une teneur fort élevée en sulfates, on ne peut donc pas s'attendre a trouver de l'eau satisfaisant aux exigences de la construction. Nous avons constaté maintes fois que les eaux de deux puits fort rapprochés l'un de l'autre fournissent de l'eau de qualités essentiellement différentes. Pour cette raison l'eau de chaque nouveau forage doit être soumise à l'analyse.

Les analyses de certains faits observés, tels des changements de la qualité dus à la structure géologique ou l'effet d'une pollution industrielle sur la qualité des eaux d'une région, la différentiation par régions de divers points de vue, conclusions à tirer au point de vue de l'hygiène, ne pourront se faire qu'au cours de l'utilisation des cartes dans la pratique.

GROUNDWATER-MAPS DEVELOPED IN THE GEOLOGICAL SURVEYS NIEDERSACHSEN AND NORDRHEIN-WESTFALEN OF THE FEDERAL REPUBLIC OF GERMANY

H. KARRENBERG*, W. NIEHOFF *, F.PREUL ** & W. RICHTER **

ABSTRACT

The Geological Surveys of Nordrhein-Westfalen and Niedersachsen have developed hydrogeological maps of different scales.

H. KARRENBERG and W. NIEHOFF developed a method for representation of groundwater conditions on maps on a scale of 1 : 25.000 whereas W. RICHTER and F. PREUL compiled hydrogeological maps on a scale of 1 : 100.000.

The maps 1 : 25.000 mainly concern regions with flat strata dissected by faults, extension and relief of groundwater base, hydrological positions of the aquifers and series of hydrological sections. Maps of smaller scale attached to the above maps represent further hydrological data, i.e. plans of the groundwater table, plans concerning the depth of the groundwater below the surface, chemical conditions a.s.o.

A method for clear representation of chemical data only, is developed by F. PREUL on maps 1 : 25.000. This method has been applied also to the above mentioned maps.

The maps on a scale of 1 : 100.000 have been developed for regions of quaternary and undisturbed tertiary deposits and for the mesozoic hill region of saxonian structure.

In regions of quaternary deposits the aquifers have been demonstrated by lines of different kind and direction, and by colour. Thereby the hydrological position as well as available water-yield of the different aquifers are considered mainly. Furthermore the representation concerns amongst other data of the depth of the aquifers, contours of the groundwater table, springs and their outflow, data concerning chemism of the groundwater a.s.o.

The representation of the mesozoic hill region is developed out of the latter maps. Above that, as far as tectonical disturbed regions are concerned the maps give mainly relations between structural and groundwater conditions.

Since many years trials have been made in different countries in order to produce maps concerning groundwater.

Although all these maps show important details, up to now there is no method for representing all factors concerning groundwater in a right mutual proportion.

In the last years geological surveys of the Federal Republic of Germany have again started to discuss the question about the method of representation of groundwater conditions in maps. It has become necessary to put in order the steadily increasing number of hydrogeological dates and to create a base for scientific considerations of groundwater problems. Furtheron the practice demanded bases for systematic exploration as the water-supply rapidly increases depending on the growing population and the progressing industrialisation.

The geological surveys of Niedersachsen and of Nordrhein-Westfalen, that means the Amt für Bodenforschung in Hannover and the Geologisches Landesamt in Krefeld, in permanent cooperation with the other geological surveys of the Federal Republic of Germany, have elaborated new methods for representation of groundwater conditions in maps for regions, which are of great economical interest.

With regard to the representation of the groundwater balance, especially of the

(*) Geologisches Landesamt Nordrhein-Westfalen, Krefeld.
(**) Amt für Bodenforschung, Hannover.

dynamics of the groundwater, the maps still contain some shortcomings resulting from the fact that necessary dates are not available in a sufficient number or can be obtained for small areas at a considerable expense only.

The aim of our geological surveys is to remove these defects and compile groundwater-maps which represent all data.

For those maps, different scales have been chosen according to purpose. Detailed scientific problems or special practical tasks demand a scale as big as possible, that means at least 1 : 25.000. For survey-maps usually a smaller scale, for example 1 : 100.000, is sufficient. This is an advantage in so far as printed maps for large regions can be published at a small expense, whereby the maps still can be used for many practical purposes.

The german topographical maps suitable for representation of hydrogeological data are on the scales 1 : 5000, 1 : 25000, 1 : 100.000, 1 : 300.000. This fact was co-determinant for choosing the above mentioned scales.

Groundwater maps, Scale 1 : 25000, as developed by Geological Survey of Nordrhein-Westfalen in Krefeld.

(H. KARRENBERG and W. NIEHOFF)

The large natural groundwater occurences in the area of Nordrhein-Westfalen were occasionally overstressed by intensive population and industrialisation during the recent years. Rising difficulties forced the Geological Survey into a systematic hydrogeological exploration and official cartographical representation. Therefore, since 1946 groundwater maps, scale 1 : 25000, have been compiled in great parts of Nordrhein-Westfalen. For relatively simple geological conditions (as for instance middle and northern Westfalen) and for the only purpose of planning for the use of groundwater reserves the maps are worked out more simple than in other parts with more complicated conditions and where special problems are of great interest. Despite the different kinds of representation in some parts of the country, the maps obviously correspond to each other in order to complete the simpler ones if desired. The restriction of the working programme is, at the moment, necessary by economical reasons.

The planned groundwater lowerings in the brown-coal area of the Niederrhein Basin gave a great impulse to the hydrogeological mapping. With a great amount of individual data a map (scale 1 : 25000) was produced there by intensive compilation, single folios of which are already printed.

Supposition for producing maps of that kind is collection and evaluation of all hydrologically important data down to a depth of at least 200-300 meters, such as results of former borings, existing level plans and pumping tests, statements about real production and its influence to the surrounding area, and finally research upon permeability and storage capacity as well as chemical investigations of the groundwater. Extensive geophysical explorations, carried out during the recent years, were also used.

Very often the underground is divided in several groundwater horizons. Each one has to be examined separately, and the probable connection has to be explored. Faults have effected the strata and perhaps partly caused different groundwater conditions in the separated blocks. Another complication is the salinity of the deeper groundwater. There are so many various facts and characterisations, that it is impossible to enter all of them on one map only. Therefore it was necessary to produce a main map with a horizontal projection plan, scale 1 : 25000, and 2 section maps —

geological and hydrological — of same scale, i.e. 3 sheets for each folio. Furthermore a larger amount of individual representations, scale reduced to 1 : 100.000, was arranged on the margin of the 3 sheets. Such an arrangement permits a better explanation of the maps, which were also provided for use of non-geologists. In case of complicated geological conditions, a representation on section maps only has proved insufficient.

On principle, zones of incomplete data were left blank to prevent incorrect correlations. Due to a careful manner of plotting, future results (i.e. new borings) will only complete or modify but not fundamentally change the interpretation. Districts, on the map appearing as blank areas, indicate where special studies have to be done in order to get a complete picture. The method of representation is the result of intensive experiments, carried out during several years.

The compilation of the various folios is always based on the graphic representation of all borings in form of vertical sections. On some maps (ca 130 km^2 each) up to 3000, on other maps, however, only a few hundred borings had to be elaborated.

Greatest value was set to a horizontal projection of hydrogeological facts *(Sheet A)*. It represents — as far as possible — by lines of equal level the orientation relating to space of the hydrogically important limits (groundwater bases and roofs as well as strata with varying impermeability). The representation interval approximately corresponds to the fault-space of the geological expression. Only numbers of altitude related to sea-level are given at the boring points, when the distance of the boreholes is too wide. For a better understanding a second number at the boring points indicates the thickness of the different aquifers. Different colours of the numbers of altitude and contour lines (hatchings) show the stratigraphic position of the stratum concerned, whereas the proved limit of extension appears as a boundary-line of same colour. The amount of underlinings indicates the coordination of the strata to the different groundwater floors. Besides, the groundwater base of the first floor is (in opposition to the deeper ones) made distinguishable by continuous contour lines or hatchings resp., and stressed by graduated areal colours. The topography of the official topographical map is imprinted in light-gray colour.

A map showing the prospective reserve of the aquifers is placed on the margin of Sheet A of the brown-coal mining district. The possible daily production of single wells is estimated on the basis of known long-term productions, according to degrees of prospective reserves, and represented by coloured areas. The petrography of the aquifers appears as a black/white-drawing. This map was attended with severe difficulties, for there are still too few particulars about intake areas and renewal of groundwater.

On further secondary maps the permeability of the surface layers in regard to the importance for the groundwater renewal is estimated, as well as lack of groundwater for agricultural cultivated plants. A lot of 2 meter-borings carried out during the geological exploration gave the base for these particulars. The more simple maps (of the Muensterland or other districts) do not have any secondary maps yet.

A second map *(Sheet B)* shows typical geological sections (length 1 : 25000, height mostly 1 : 3000), as many as possible, if the geological conditions seem to make it useful. In some areas the series of strata is so uncomplicated, that such an expense would not be worthwhile. In other areas, however, the various stratigraphical units are interpreted. The geological age is indicated by areal colour, the petrographic structure by black/white symbols.

A secondary map in black/white-drawing shows the geological conditions in greater depth, as far as they are known by results of deep borings (2-300 meters). In some cases they are important for hydrological problems. Another secondary map represents the chemical conditions of the groundwater, each floor separated, according to the method of F. Preul.

The third map *(Sheet C)* illustrates in hydrogeological sections the most important hydrological properties of the different layers, that is groundwater bearing strata, impermeable strata and areas lacking groundwater are areally coloured, possible capacity of the aquifers is represented by petrographic symbols and some inscriptions of k-indexes. This gives a very clear idea of the division of the groundwater floors. Rocks without a uniform groundwater-distribution are made distinguishable in a special way. Normal groundwater levels without pressure and artesian levels are indicated by red lines.

Secondary maps, placed on the margin of the main map C, show two groundwater level plans, based on official measurings of the Government-board, including a minimum and a maximum water level throughout a characteristic year of observation, furthermore groundwater thicknesses of the top horizon and of the level distance below surface, which, in the main, were developed for engineers. Any secondary map is areally coloured. These secondary maps also were made for the brown-coal mining district and its surrounding area only, all the more so as the official measurings of groundwater levels were extended to a larger part of the country during the most recent years only.

So far the following maps have been compiled:

1) Extensive representation, as already mentioned: 16 folios,
2) Simple form: 64 folios.

Four folios of the category mentioned under 1) have already been printed.

The groundwater maps have proved their value in many respects. First of all, in the Muensterland and the Niederrhein District, they gave very valuable data for areal groundwater exploration and for prediction of districts, which are covered by pleistocene deposits (boulder clay, loess etc.). Large groundwater occurences, unknown or only little known, were found, which additionally can be exploited for the water supply of big towns. So the maps are an important basis for the purpose of planning of the water supply.

Besides, the maps are used for the solving of certain hydrogeological problems, such as prediction of extent and influence of deep lowerings for water works or for the ultra-deep openpit mines already started west of Cologne (250 meters deep). The effect of such extraordinarily deep lowerings has to be known in advance as far as possible, which is often very difficult, for it does not concern homogeneous material, but the whole series of strata is divided by several clay horizons. Also the impermeability of fault zones is, above all, not ascertainable. Especially only an exact representation of the geological conditions permits the recognisation of hydraulic relations between the different floors and gives particulars as to where there is only incomplete knowledge about the hydrogeological conditions and where additional new borings are necessary. Salted groundwater rises — especially at fault zones — and reduces the usefulness of the prospective aquifers. A cartographic representation gives a good view to the salinity of the deeper underground and its effect to the exploitation of groundwater. Conditions are becoming even more difficult in mining areas.

Also the problem of groundwater protection can be predicted much better, if we have maps of that kind. During the recent years such questions became more and more important in intensively industrialised areas, particularly when laying pipelines, industrial waste water pipes etc.

Finally the maps give the necessary information for further borings, especially for placing new exploration borings and the depth of the water-prospective strata.

Groundwater maps, scale 1 : 100.000 as developed by the Geological Survey of Niedersachsen in Hannover.

(*F. PREUL and W. RICHTER*)

The hydrogeological maps on the scale 1 : 100.000, hitherto developed in Niedersachsen, refer to the region of NW-Germany which is filled with quarternary deposits and to the adjacent mesozoic hill-region of saxonian tectonical character in the south.

1.

Groundwater conditions in regions with quarternary deposits are represented predominantly on the base of boring results. As the quarternary deposits are not very extended but vary in extension, depth and thickness and as the boring net differs the groundwater maps partly represent the details and partly adhere to a representation of the area in the large.

The representation of the groundwater-conditions reaches a depth of about 300 m below the surface. With reference to groundwater-conditions in regions with quaternary deposits only regions with wide-spaced aquifers and aquifuges can be represented in detail. Regions in which aquifers and aquifuges change closely (i.e. moraine terminale) have to be represented in the stated scale 1 : 100.000 by summarized sign, therefore these regions are not dealt within the following.

In the regions with wide-spaced aquifers and aquifuges the groundwater-conditions are represented in quaternary deposits as well as in lower based tertiary and mesozoic deposits. The latter are only represented if they are not very much displaced.

The various aquifers are designed by straight lines of different kind, direction and colour. The kind indicates lithology and age, the direction indicates the storey and the colour indicates the water-yield.

The aquifuges in the underground are not represented. Their spread and depth result indirectly from the data of the aquifers respectively storeys.

The data about the available water-yield are not exact. They have been gathered empirically from normally constructed vertical wells in which pumping causes a tolerable table-depression.

The depth relation of the groundwater is demonstrated a) by depth-contours of the groundwater table above sea level (NN) within the first storey and b) by number-columns which show at specially marked points, the depths of the storeys f.i.

+ 18/+ 5	I.	storey between	+ 18 m NN and + 5 m NN
— 2/—10	II.	» »	— 2 m NN and — 10 m NN
— 12/—18	III.	» »	— 12 m NN and — 18 m NN

a.s.o.

Furthermore the maps show dislocations and zones of fissures in form of jagged lines. They are coloured according to the width of the fissures and the water-yield therewith connected.

Chemical data of the groundwater are given by differently coloured signs standing always on the line which marks aquifer and storey.

Boggy regions the first storey of which carries water rich in iron with humic combinations are marked by widely spaced brown-coloured signs.

Occurences of mineral waters in wells or pits are given by spotted coloured signs.

All springs are also registered. Their use or their non-use as well as the amount of their outflow is marked by coloured semi-circles.

Technical establishments in connection with groundwater are also marked on the map; for example waterworks and their output im m³ per year, pipelines etc.

In order to make the map accurate all borings are registered in the following system:

Final depth less than — 300 m NN; Quaternary not perforated.
» » » — 300 m NN; Quaternary perforated
» » at — 300 m NN or deeper

Areas with many drillings are surrounded by a coloured line instead of marking the borings by points.

Hitherto one sheet of the previously described map comprising about 1500 km² of the Emsland has been printed.

Two other sheets are ready for printing in the near future. Attached to all maps are explanatory notes describing the hydrogeological conditions of the represented area. Partly, these descriptions are based on large-scaled special maps, on data about pumping tests, on tables of water-analyses etc.

2.

The groundwater conditions in the Middle-German Hills of saxonian tectonical character are represented in a map similar to the previously described region with quaternary deposits in order to aim at a certain unity. Some alterations and complet-ions with respect to the different geological conditions are necessary.

The map represents the hydrogeological conditions down to 200 m underneath the surface. This boundary has been chosen because borings for the exploitation of groundwater under this depth are usually uneconomic. Above that the ground-water in these regions contains soluble substances from the salt and gypsum beds of mesozoic and paleozoic deposits. However, the limit depends on the local geological conditions and may therefore occasionally vary.

The number of series of water-bearing strata, the thickness of which is small and unimportant and which are situated one under the other is often so high that it is necessary to place them into groups.

The groups are seperated from each other by deposits of aquifuging beds of bigger thickness. This arrangement does not always agree with the stratigraphy.

The above mentioned strata-groups are signified on the map by letters.

The relation between groups and stratigraphical arrangement may be seen from a column-profile attached to the map.

Furthermore this legend contains statements concerning the petrographical qualities, the thickness and the magnitude of the permeability of all parts of the deposits.

The petrographical quality of the fissured rock beds which are predominant in the represented group is given by different hatchings. The water bearing rock beds closest to the earth's surface (first groundwater storey) appear on the map as a shaded plane. The deeper groups of rocks are represented by hatching-lines the direction of which indicating the number of groups above.

The representation can be limited usually to 2-3 groups of aquifers; the grouping has to be chosen accordingly.

Similar to the map recently described the colour of the hatchings refers to the available water-yields of one aquifer group. The map is based on experiences on wells. Three types of water-yields can be distinguished. Furthermore rocks with changing water conductivity, i.e. karsted limestones are specially marked.

As fissures and the water conductivity therewith connected strongly change the data about yields have to be understood in the average.

The permeability of the deposits that are situated above the first groundwater

storey is given by light colours covering each individual plane: There are three shadings for easily permeable, moderately permeable and impermeable layers.

Furtheron the tectonical structure of represented rock groups is marked by contour lines combining points of equal position to sea-level at the base of the rock groups. With the help of an inclination-scale the dip of the layers can be plotted.

Chemical qualities of the groundwater, outcroppings, level-lines and technical data about water output and pipelines are given in the same manner as in the map mentioned under 1).

For clearness the map is provided with vertical sections.

One copy of the above described map is existent as script for an area of about 1000 km² in the region of Hildesheim. A cutting of this map was printed on probation in a small edition.

A METHOD OF MAPPING CHEMICAL DATA OF GROUNDWATER

(F. PREUL)

In completion to the groundwater maps described under Nos. II and III maps showing the chemical qualities of the groundwater are compiled, the object of which is to represent figuratively analyses of water. The scale of the maps varies. This kind of compilation allows to compare and recognise the chemical relation between rock and groundwater.

Each analyses resp. each series of analyses made of a water sample derived from one point of the same waterbearing rock, is represented as a single figure in the map. Analyses on water from one and the same point from the different groundwater storeys are represented separately.

Each figure represents a diagram consisting of 6 columns standing side by side. They stand for the 6 most important chemical data of the area registered. For a clear representation a few data of analyses only have to be chosen because not all data are important everywhere and complete analyses are mostly not available. The height of the columns represents their degrees of size in an almost logarithmic scale. The size of the diagram of the single analyses resp. series of analyses is limited to 8 × 8 mm in order to save space.

For the purpose of simplifying the make of the diagrams as well as to estimate better the height of the columns a square with 6 vertical fields and one horizontal middle line is reprinted by stamp.

This middle line stands for the important boundary value of the different chemical data. If the data of analyses surpass this line and if the H_2O is required for central supply of drinking water then a dressing is necessary.

Also the maximum values of chemical data observed vary; the upper limit is fixed arbitrarily for reserving as much space as possible for concentration areas which are of practical importance.

For these reasons different scales are needed for each column.

The following table is an example for the selection of the limits and the maximum values of chemical data represented on one of our chemical maps.

	limit	max. value
1. sulphate (SO_4'')	200 mg/l	1000 mg/l
2. chloride (Cl')	200 »	1000 mg/l
3. iron (Fe)	0,2 »	80 »
4. total (whole) hardness	18°D.H.	80°D.H.
5. carbonate hardness	18°D.H.	(80°D.H.)
6. lime-aggr. carbondioxide	0	50 mg/l

In the above case 4 different scales have been necessary for the 6 columns represented. These scales have been developed from the following functions as follows: column 1 and 2, SO_4'' and Cl'

$$y = 66{,}67 \, . \, (e^{0{,}3466 . x} - 1) - 16{,}67 \, . \, \sin\left(\frac{\pi}{4} . x\right)$$

» 3, Fe

$$y = 0{,}0005025 \, (e^{1{,}497 . x} - 1) + \cos\frac{\pi x}{4}$$

» 4, and 5 whole hardness and carbonate hardness

$$x = 3{,}238 \, . \, \ln\left(1 + \frac{y}{7{,}365)}\right)$$

» 6, lime-aggr. carbondioxide

$$x = 10 \, . \, \ln\left(1 + \frac{y}{103}\right) \qquad x > 0$$

If there is a balance between lime and carbondioxide then the field below the middle line is filled. In case of more carbondioxide this quantity is represented above the line.

As the chemism of groundwater mainly depends on the geologic-petrographical conditions of the intake area (area subject to rainfall) and of the aquifer, the water bearing rock from which the sample has been gathered is represented by colouring the sections of each column below the middle-line. The column sections above the middle line are marked in a bright red colour.

Therefore it becomes possible to make conclusions—by comparison of analysis data of samples taken in the same aquifer—as to the qualities of groundwater in those regions where the same rock of the same petrographical nature exists.

If there are more groundwater analyses for one point of the same aquifer then the height of the column represents the observed maximum values whereas the minimum values are marked by thin white lines giving thus the reach of oscillation.

For better comparison of groundwater analyses, special symbols or figures are added. Thus f.i. the stress with reference to the quantity taken from the well is represented. Moreover, possibilities of modification of the groundwater by seepings from the surface f.i. soluble matter of all kinds and waste water, are marked.

A supplementary text book belongs to the map containing complete analyses and different additional statements.

HYDROGEOLOGICAL MAPS AND THEIR ROLE IN ESTIMATING THE WATER-BEARING CAPACITY OF ROCKS AND SUBSOIL WATER RESOURCES

M. V. CHURINOV

ABSTRACT

1. A hydrogeological map reflects the distribution of aquiferous and watertight rocks, composition and hydraulic features of different types of underground waters. In the USSR hydrogeological maps of a scale less than 1 : 1 000 000 are compiled on the basis of existing maps. The maps with a scale from 1 : 500 000 and larger are compiled on the basis of field data.

2. The maps of a 1 : 1 000 000 scale and less are a survey; mostly they contain information about the distribution of underground waters and are a starting point in planning more thorough hydrogeological investigations. The maps of the scales 1 : 500 000; 1 : 200 000 and 1 : 100 000 are called general. They contain information about the distribution of ground and artesian waters, their chemical composition, general mineralization, sometimes about the depth of different aquifers, and, as a rule, contain a quantitative estimate of a run-off of underground waters into separate wells.

Hydrogeological maps of a scale larger than 1 : 100 000 are of special character and differ from small-scale maps by detailed information about the quality of underground waters and different kinds of their resources.

3. Hydrogeological maps of the scales 1 : 500 000, 1 : 200 000 and 1 : 100 000 are regarded as the state hydrogeological maps which are compiled for the whole territory of the Soviet Union.

4. Besides the general and the special hydrogeological maps compiled in the Soviet Union there are: maps of ground waters, of artesian waters, both artesian and ground waters, of mineralization and chemical composition, the main aquifers, depths of occurrence, water abundance. In some cases there are compiled maps of thermal waters, mineral waters, the forecasts of watering mineral deposits.

Tables on the maps give data about the distribution area of aquifers or complexes, their thickness, average porosity, average filtration coefficients, water levels in wells and approximate volumes and expenses of underground waters for every aquifer computed from these data.

A hydrogeological map is a variety of a geological one drawn to characterize subsoil waters running in the rocks. Subsoil waters are very dynamic and have a close connection with the surface waters and atmospheric precipitations; therefore, when making a hydrogeological map, it is necessary to show the distribution of subsoil waters not only in parallel to the surface of the earth, but also in the vertical direction. This specific feature of mapping which takes into account the dynamics and depth of subsoil waters distinguishes in principle between a hydrogeological map and a geological one.

The hydrogeological map is drawn on a conditioning geological map of appropriate scale, but if there is no geological map, the study of subsoil waters should be preceeded by or carried out simultaneously with an investigation of the geological structure of the territory.

Regardless their scale all hydrogeological maps give complex characteristics of subsoil waters, i.e. show their different aspects, such as, the interaction between the running subsoil waters and the rocks which bear them. As a rule, hydrogeological maps show the distribution of the subsoil waters which are concomitant to water-bearing complexes or levels, the geological age of the rocks which contain them, the lines and zones of tectonic disturbances, the mineralization or anionic type of chemical composition of subsoil waters, the hydraulic properties and water reference points: holes, wells and springs.

In the Soviet Union maps are made to show subsoil waters, water-bearing capacity of quarternary rocks, pressure (artesian) waters, and water-bearing capacity of pre-quarternary rocks. Depending on its scale, the contents and load of a hydrogeological map are different and, in addition to the above mentioned characteristics, large-scale maps (larger than 1 : 500,000) indicate water abundance of rocks, the depth at which subsoil waters are deposited, pressure, number of storeys in which the subsoil waters are distributed in the vertical direction, etc.

Hydrogeological maps with a scale of 1 : 500,000 and less often divide the territory into regions for water-bearing capacity of pre-quartenary deposits, as a rule, on the basis of geological and structural principle and for water-bearing capacity of quarternary deposits or for subsoil waters on the basis of geomorphological principle. The singling out of hydrogeological regions is the final stage in studying the subsoil waters of this or that territory, i.e. synthesis of all the data obtained, and is of great scientific importance, because it shows, for each separate region, the specific features of the conditions in which the subsoil waters are formed, fed move and discharge and, consequently, determines the direction of engineering measures to be taken to make practical use of the subsoil waters or to struggle against them.

In the Soviet Union hydrogeological maps are divided into the following three groups according to their scale:

Survey hydrogeological maps with a scale from 1 : 500,000 and smaller

General hydrogeological maps with a scale from 1 : 200,000 to 1 : 25,000

Specialized hydrogeological maps with a scale of 1 : 10,000 and larger

The survey hydrogeological maps are in turn subdivided into large-scale (1 : 500,000), medium-scale (1 : 1,000,000 to 1 : 1500,000) and small-scale (1 : 2,500,000 to 1 : 5,000,000) maps.

The large-scale survey hydrogeological maps are designed to show the hydrogeological conditions of some limited territrory covering a definite geological and structural element-hydrogeological region or part of it, for example Podmoskovny Basin, Dnieprovsko-Donetsky Depression, etc. These maps are used when planning detailed hydrogeological investigations and in some cases, if the geological structure of the region is simple, they may serve as the basis for the first stage of planning large-scale engineering measures. When there are no maps of larger scale, they may be used as a guide for developing bore holes for water.

The medium-scale survey hydrogeological maps are designed for giving general characteristics of subsoil waters of a vast territory which includes a system of geological and structural elements that form platforms or geosinclines or both of them, e.g., European Part of the U. S. S. R.

These maps are used for clearing up some questions of subsoil waters formation when planning hydrogeological work to be done to make practical use of the subsoil waters and finally as a reference material to decide questions of regional hydrogeology.

The small-scale hydrogeological maps are designed to show general hydrogeological conditions of the whole territory of our country. These maps first and foremost should serve as the scientific basis for working out a theory of subsoil waters formation on the basis of finding out the laws that govern distribution, feeding, movement and discharging of subsoil waters, the laws that govern changes of salt and gas composition, zonality and hydrothermics and finally for revealing the principal factors of prognosticating the deposits of useful minerals. These maps should also be the basis of perspective planning of investigations to be done before carrying out various measures of economic significance to make practical use of subsoil waters or to struggle against them. These maps can also serve as training appliances for specialized schools of higher and secondary education.

At the same time the small-scale survey hydrogeological maps should serve as the basis for creating monographs devoted to subsoil waters of the Soviet Union.

Thick quarternary deposits and considerable amounts of subsoil waters which can be used for practical purposes are also mapped. The small-scale survey hydrogeological maps with a scale of 1 : 2,500,000 should give characteristics of the distribution of water-bearing and water-resisting rocks conformably to the divisions of a stratigraphic scale, while maps with a scale of 1 : 500,000 conformably to the systems.

The medium-scale survey hydrogeological maps with a scale of 1 : 100,000 to 1 : 1,500,000 should give characteristics of subsoil waters in compliance with the degree to which they have been studied, i.e., for some regions conformably to the divisions, while for other regions, which have been less studied, conformably to the storeys.

The survey maps should show the distribution of water-bearing and water-resisting rock complexes, number of storeys of water-bearing layers in the vertical direction, mineralization, temperature and chemical type of waters, hydrogeological regions, boundary of congelation of many years and water reference points.

The general hydrogeological maps show the distribution of the next-to-the surface water-bearing level and levels situated at different depths. They contain data on water abundance round the springs, holes and wells (specific yield), as well as show the depths at which subsoils waters are found, number of storeys of water-bearing rocks, including the head race if it is of practical significance, conditions of feeding and drainage, pressure and the main direction of the movement of the subsoil waters, water reference points, tectonic zones and breaks, lakes, rivers, water bodies, etc. These maps are used for substantiating measures to be taken to exploit or to struggle against subsoil waters at the stage of reporting technical and economic advantages of the region, although in some cases, when geological structure of the region is simple, they are used at the stage of marking projects of future work.

The specialized hydrogeological maps with a scale larger than 1 : 10,000 are purposefully developed to substantiate specific engineering measures to be taken to make practical use of the subsoil waters or to struggle against them and, in contradistinction to maps of smaller scale, they give a detailed information on those characteristic features of the subsoil waters which are most important for carrying out the planned measures, e.g. the depth of the table of the subsoil waters, direction of their flow in the contours of the water table, abundance of water aflux in separate places found from the results of pumping, etc. These maps are used for carrying out specific measures at the stage of planning future work and often even at the stage of making a technical project.

In the Soviet Union extensive use is made of hydrogeological maps with a scale of 1 : 500,000; 1:200,000; and 1:100,-000. Major part of country's territory is mapped in these scales. Maps with a scale of 1:50,000 and 1:25,000 are drawn in compliance with the regions undergoing specific economic development, while maps with a scale of 1:10,000 and larger only at the places where a detailed study of subsoil waters is going on to obtain necessary data for carrying out engineeering measures to be taken to exploit the subsoil waters or to struggle against them.

In the Soviet Union various types of hydrogeological maps are developed. These are the maps of the next-to-the surface water-bearing level, of subsoil waters, artesian or pressure waters, fresh waters, mineral and thermal waters, maps of mineralization of the subsoil waters, maps of important (for water supply) water-bearing levels, maps of the depths at which subsoil waters are found, water abundance prognostication of water amounts at the deposits of useful minerals and other maps to meet the requirements of various branches of the national economy of the U.S.S.R.

All the above mentioned types of hydrogeological maps give in different details the characteristics of water bearing capacity of rocks. Depending on the purpose

of the map and on its scale the water-bearing capacity is shown either as a whole complex or in any individual characteristics.

When water-bearing capacity is characterized, most of hydrogeological maps give qualitative and quantitative estimation of subsoil waters based on investigating them round the springs, wells and holes. Graphically this estimation is expressed, as a rule, either in fugures determined near the excavations to show concrete values of the water afflux in each or by additional singling out the areas on the basis of the adopted gradations of the specific yields of the holes wells or springs.

Thus in the estimation of water-bearing capacity of rocks on the basis of separate excavations a hydrogeological map plays an important rôle, because it allows a quantitative orientation in the character of the water-bearing capacity of rocks of different age not only in parallel to the surface of the earth (bearing) but also in the vertical direction. Besides its scientific value as a synthetic document which shows the laws of distribution, quality and degree of abundance of subsoil waters, this map is of great practical importance for it is used as the basis for scientific planning of the future engineering measures to be taken to make use of the subsoil waters. In quite different position is the question of the rôle of a hydrogeological map in the estimation of the resources of subsoil waters. This question is hitherto in the embryonic state, although some attempts in this respect have already been made by Soviet scientists.

Before turning to the question of the rôle of a hydrogeological map in the estimation of the resources of subsoil waters we shall briefly dwell on the notion of «resources» or « stocks ».

In the Soviet Union not small attention is paid to the classification of the resources of subsoil waters on the basis of natural indications. A number of works by I.M. Butov ([4]), N.K. Ignatovich ([5]), F.P. Savarensky ([14]), K.L. Mackov ([10, 11]) M. E. Altovsky ([1]), B. I. Kudelin ([8]), G. I. Kamensky ([7]), N. A. Plotnickov ([13]), M. P. Semienov ([15]), E.F. Tamm and M.P. Tolstoi ([17]) give a definition of the notion of subsoil water resources. Not launching into a detailed consideration and comparison of the classifications made by the above mentioned authors, it is necessary to note that almost all of them single out in the same way several types of resources and the differences found in the differences found in the definitions mainly bear only terminological character. In their classifications all the authors note the principal features peculiar to subsoil waters: their movability and renewal. Therefore two main categories are considered: volume and consumption of subsoil waters. N.A. Plotnickov with participation of G.V. Bogomolov and G.N. Kamensky ([12]) singles out a) natural resources — consumption of subsoil currents, b) regulated resources in the zone of fluctuation of the level of subsoil waters, c) age-old stocks — below the zone of fluctuations of the level of pressureless waters and within the limits of the whole layer of pressure waters, d) exploitation resources — consumption of a subsoil flow which can be obtained for a certain period of time by capping constructions.

F.M. Bochever ([3]) gives the following classification of subsoil waters for water supply purposes: a) Natural stocks (resources)— static and dynamic, b) Exploitation stocks (resources).

The natural resources are called static if it is the volume of subsoil waters in the pores and cracks of a water-bearing bed, and dynamic if it is the consumption of subsoil waters running through the bed in natural conditions. The exploitation resources are the consumption of subsoil waters of a water-bearing level or complex within a difinite area of its bedding by a water pumping installation during the whole planned period of its operation.

The widely used term «Static resources» does not express what is taking place

in reality, because it is impossible to imagine static subsoil waters in the rocks. Instead of static resources it is better to use the term «full volume of gravitational waters» of the bed.

Depending on its scale and actual material, a hydrogological map should show either natural or exploitation resources.

Survey maps should show natural resources, while general maps and the more so specialized ones should show exploitation resources.

To estimate the exploitation resources of subsoil waters, it is necessary to study a) the geological conditions of the region, b) the size of the water-bearing level planned for exploitation, c) the most important feeding sources, d) the connection of the subsoil waters with the surface ones (rivers, water bodies), and e) the value of natural consumption and of the full volume of gravitational waters. To estimate the natural resources of subsoil waters with an object of showing them on survey hydrogeological maps, it is necessary, on the basis of the analysis of the materials given by the bore holes and by experimental pumping, to calculate by method of constructing hydrogeological cross sections the initial data on the area in which each water-bearing level or complex is distributed, on their angle of slope regarding the horizon, on the average thickness and length of the water-bearing layers, and on the value of hydraulic inclination of the current with a medium-suspended filtration coefficient.

One of the methods of calculating the natural resources of groundwaters is the well-known method of determining the consumption of a subsoil current from the Darsy equation.

All the initial data, on which the calculation of the resources of subsoil waters is based, should be arranged into tables and placed under the legend of a hydrogeological map developed to show the resources of groundwaters. In conformity with the purpose of the maps of subsoil waters resources the value of natural resources should be shown in conventional colours according to selected gradations with a stratigraphic classification of subsoil waters of the upper water-bearing level left under the colour. The lower water-bearing levels accounted by the summary estimation of the resources should be shown by indices placed in the margins of this or that tone. Another method of regional estimation of the natural resources of artesian waters in the regions with a developed network of hydrological posts is the method of average water balance of many years offered in 1951 by prof. P. I. Kudelin ([8]). The method is based on solving the equation $\pm W_0 = X_0 Y_0 Z_0$ where

W_0 is the deficit or surplus of water in the areas of feeding and discharge, i.e., natural resources;
X_0 the average value of precipitations during many years;
Y_0 the average value of river discharge during many years;
Z_0 the average value of evaporation during many years.

The whole territory is divided into a number of water collecting basins of principal rivers and their tributaries, running in the region, and according to these basins, on the basis of observations over their consumption and of comparing the results of the observations with the value of precipitations a conclusion is drawn whether the given basin exerts feeding or draining influence on the resources of subsoil waters.

The hydrogeological maps of subsoil water resources developed by either method will sharply increase both the scientific and practical significance of maps and will make them a document to be widely used in the national economy.

Moreover the maps of subsoil waters resources will be a new step forward in the development of a young science of hydrogeology.

REFERENCES

(1) M. E. ALTOVSKY. Metodika Gidrogeologicheskih Izyskanii dlia Tselei Vodosnabzhenia, ONTY, 1936.
(2) M. E. ALTOVSKY. Classification of the Exploitation Resources of Subsoil Waters. *Sovietskaya Geologia*, N 19, 1947.
(3) F. M. BOCHEVER. Classification of the Resources of Subsoil Waters for the Purposes of Water Supply, *Sovietskaya Gologia*, N 61, 1957.
(4) I. M. BUTOV. To the Question of Determining the Resources of Subsoil Waters. Trudy I Vsesoyuznogo Gidrogeologicheskogo Sjezda, Sb 6, 1933.
(5) N. K. IGNATOVICH. Methods of Calculating the Resources of Subsoil Waters of an Artesian Basin. *Razvedka Nedr*, N 8, 1937.
(6) Instruktsia po Primeneniyu Klassifikatsii Exploatasionnyk Zapasov Podzemnyh Vod. Gosgeolitizdat 1952.
(7) G. N. KAMENSKY. Poisky i Razvedka Podzemnyh Vod. Gosgeolitizdat, 1947.
(8) B. I. KUDELIN. The Principles of Regional Estimation of the Natural Resources of Subsoil Waters (Avtoreferat Doktoskoi Dissertatsii; MGU im Lomonosova, 1955) Doklady Akademii Nauk SSSR 1956 VIII, N 2.
(9) F. A. MACKARENKO. Classification of the Stocks and Resources of Subsoil waters. Trudy Laboratorii Gidrogeologicheskih Problem A. N. SSSR v. III, 1948.
(10) K. M. MACKOV. Methods of Calculating the Resources of Subsoil Waters of an Artesian Basin. *Razvedka Nedr*, N 23, 1936.
(11) K. M. MACKOV. Methods of Calculating the Resources of Subsoil Waters in Large Hydrogeological Regions. *Razvedka Nedr*, N 8, 1937.
(12) N. A. PLOTNICKOV with participation of G. V. BOGOMOLOV and G. N. KAMENSKY. Klassifikatsia Resursov Podzemnyh vod dlia Tselei Vodosnabzenia i Metodika Proschta. Gosgeolitizgat, 1946.
(13) N. A. PLOTNICKOV. The Principles of Estimating the Resources of Subsoil Waters for the Purposes of Water Supply. *Sovietskaya Geologia*, N 19, 1947.
(14) F. P. SAVARENSKY. Gidrogeologia. Gosgeolitizdat, 1935.
(15) M. P. SEMIENOV. The Basic Definitions and Classification of the Resources of Subsoil Waters for the Purposes of Water Supply. *Sovietskaya Geologia*, N 19, 1947.
(16) E. F. TAMM. Methods of Calculating the Resources of Artesian Waters. *Razvedka Nedr*, N II, 1937.
(17) M. P. TOLSTOI. Methods of Calculating the Resources of Subsoil Waters of an Artesian Basin. *Razvedka Nedr*, N 8, 1937.

METHODS OF PRODUCTION A MAP ON SUBTERRANEAN WATERS OF HESSE

Dr. FRIEDRICH NÖRING
Governmental Geologist, Geological Survey of Hesse, Wiesbaden.

Hydrograph-statistic methods to compute the amount of ground water flow (Schroeder 1955), especially by means of base flow curves, can not be applicated on little watersheds, e.g. 1 km², because gauges of surface water run-off mostly are absent for such areas. The extension of the watershed differs between high and low water. High water is nourished prevailing from the morphologic determined watershed, low water from the subterranean geohydrologic watershed. The difference may be neglected in watersheds of great extension. — On the other hand hydrogeological maps (Grahmann 1955) show in first line the effective porosity of geologic formations and the specific yields of wells. They give no answer upon the question about the real amount of ground water recharge and ground water flow.

It seems necessary to satisfy the increasing consumption of ground water in Germany by determining the exact area and the approximate quantity of subterranean water flow. The Geological Survey of Hesse (Director: Prof. Dr. Michels) has begun to develop a method of ground water mapping by field investigations. The method seems to be very obvious, but it is — after the authors knowledge — not yet described in literature. The mapping is based on field observations, measuring and collecting data. It demands furthermore combining, estimating, touching, sampling and correcting to obtain a plausible map on watersheds, infiltration areas, quantities of discharging ground water, his subterranean way and quality.

The field work begins by following all surface currents upward to the initial springs of waters network. It shall be done during summer and autumn when low water run-off predominates. All springs, effluent and influent seepages are plotted and enrolled in questionnaires. Some physical and chemical measurements, for example temperature, specific weight, conductivity, p_H-figure, shall help to determine the geological provenience. the subterranean way and the infiltration area of the outcropping groundwater. The hydrogeologist has to find out the geological position of the spring. He has to study the geological map of large scale and the field geology.

Influent and effluent seepages shall be discovered by run-off comparison of neighbouring river sections. Exact localizing is possible by colouring or making muddy the river water, thereby producing a contrast against the clear influent seepage water, by observation during ice cover, by observation of vegetation, by dipping in an electrical thermometer and may-be in future by using television camera.

In special cases when spring water seems characteristic for certain conditions detailed investigations concerning the whole chemical content of water — not only of a few contents of hygienic or technical importance — and radioactivity shall be made.

Of course all data over artificial ground water gaining, for example in wells, galleries, tunnels, ditches and pits, shall be collected and evaluated, likewise all observations on ground water level and its fluctuations.

Field-investigators, hydrogeologists and technical assistants shall work in neighbourhood to obtain data under the same meteorological conditions of an area as large as possible. The members of the team shall meet each other every evening at a joint quarter where also special instruments are kept ready when needed.

Controls and repetitions of measurements shall catch the changes under changed meteorological conditions.

Success is obtained when the sum of all single springs is identical with the whole run-off of a river in low water time.

The work shall be completed by constructing the watersheds of each spring. As a base apart from all collected data, maps of the height of aquifers, and maps of soils (pedology) are important. Soil maps show the distribution of soil types which depend from infiltration rates, ground water surface and porosity. Vice versa the soil type reveals data on infiltration rates.

Cross-sections shall be added to maps when necessary. The question of publication shall be answered at a later time.

The described ground water maps represent an inventory of available ground water bodies and their quantity. The exact plotting of springs will also guide to the discovery of geological formations and tectonic structures.

The work includes not only compiling of already known data and situations, but also basic research. Geological mentality seems to be suitable to draw right conclusions out of a mixture of exact data and suppositions.

BIBLIOGRAPHY

FERRIS, JOHN G. & A. NELSON SAYRE: «The quantitative approach to ground-water investigations». — *Economic Geology*, 50. anniv. vol., p. 714-747, Lancaster, Penna., 1955.

GRAHMANN, RUDOLF: «Die Grundwasservorkommen im Gebiete der deutschen Bundesrepublik, ihre Nutzung und ihre kartographische Darstellung.» — *Union géod. et géophys. int., Ass. int. d'hydr. scient.*, publ. 37, Assemblée gén. Rome 1954, 2, p. 356-363, 2 maps, (Louvain 1955).

NÖRING, FRIEDRICH: «Grundsätzliches betreffend hydrogeologische Karten.» — *Zeitschr. deutsch. geol. Ges.*, 101, (1949), p. 222-229, Hannover 1950.

NÖRING, FRIEDRICH: «Bericht über das Referat wissenschaftliche Hydrogeologie und Landesgrundwasserdienst». — *Notizbl. hess. L.-Amt Bodenforsch.*, 85, p. 475-478, Wiesbaden 1957.

SCHROEDER, GERHARD: «Die Grundwasserreserven der Flußgebiete. Der Zuschußwasserbedarf der Flüsse.» — *Bes. Mitt. deutsch. gewässerkundl. Jahrb.*, 13, 49 p., 50 p. tables and figures, Koblenz 1955.

HYDROGEOLOGISCHE PROFILKARTEN FÜR DAS GEBIET DER SÜDLICHEN NIEDERRHEINISCHEN BUCHT

H. BREDDIN
Aachen

Das südliche Niederrheingebiet ist der Sitz eines ausgedehnten Braun- und Steinkohlenbergbaues sowie mannigfaltiger Industrien. Seine Grundwasserverhältnisse sind daher von großer praktischer Bedeutung. Durch die im Gange befindlichen Entwässerungsmaßnahmen des Braunkohlentagebaues, die bis zu 250 m Tiefe reichen, ist eine Erforschung der Grundwasserverhältnisse besonders dringlich geworden. Dies gab der Landesregierung von Nordrhein-Westfalen Anlaß, den Bearbeiter mit der Herstellung eines 36 Blätter umfassenden hydrogeologischen Kartenwerkes 1:25 000 zu beauftragen, von dem 25 Blätter bereits vorliegen.

Im südlichen Niederrheingebiet sind sowohl die diluvialen Rhein- und Maasschotter und Sande, wie auch die unter ihnen folgenden lagunären und marinen Tertiärschichten, die dem Pliozän, Miozän und Oligozän angehören und überwiegend aus hellen Sanden und Quarzkiesen mit eingeschalteten Ton- und Braunkohlenflözen bestehen, wasserführend. Grundrißliche hydrogeologische Darstellungen wären hier wegen des Auftretens mehrerer Grundwasserstockwerke übereinander unzureichend. Die Bearbeitung und Darstellung des Kartenwerkes erfolgte deshalb in Form von Profilserien in regelmäßigen Abständen von 1 oder 2 km, die entsprechend den tektonischen Verhältnissen des Gebietes in die Richtung SW — NE gelegt wurden. Es erwies sich als zweckmäßig, für jedes Blatt 3 Typen von Profilkarten herzustellen, Nr. 1 im Maßstab 1:2 000 in Abständen von 1 km bis zu 75 m Tiefe, Nr. 2 im Maßstab 1:2 000 in Abständen von 2 km bis zu 175 m Tiefe und Nr. 3 im Maßstab 1:5 000 in Abständen von 2 km bis zu 375 m Tiefe. Solche Profilkarten geben auch dem Nichtgeologen einen guten Einblick in die geologischen und hydrologischen Verhältnisse. Von dem Bearbeiter erfordern solche Darstellungen freilich einen hohen Arbeitsaufwand. Die intensive Durcharbeitung des geologischen und hydrologischen Materials wäre indessen auf keine andere Weise zu erreichen gewesen.

Von jeder Profilkarte besteht eine hydrologische und eine geologische Ausfertigung. Für diese wurde die gleiche Grundzeichnung mit den petrographischen Signaturen benutzt, die in jeweils verschiedenen Farben angelegt wurden. In der geologischen Ausfertigung kommen die starken Ausbildungs- und Mächtigkeitsänderungen der einzelnen Schichtglieder (meist Rhythmen) klar zum Ausdruck. Die Anordnung der Profile quer zum Haupteinfallen der Schichten und senkrecht zu den Hauptstörungen läßt auch den tektonischen Aufbau gut heraustreten.

Die hydrologische Darstellung veranschaulicht die Durchlässigkeit der verschiedenen Grundwasserstockwerke in Farbabstufungen von blau bis violett. Grundwasserfreie Bereiche wurden in gelb, grundwasserstauende Schichten in orange angegeben. Die Art, Verteilung und Mächtigkeit aller Grundwasserstockwerke ist auf diese Weise leicht zu übersehen.

Als Ergänzung ist jedem Profilkartenblatt ein im Hauptgrundwasserspiegel abgedecktes Kärtchen 1:100 000 beigegeben, das die Art des obersten grundwasserführenden Gesteins, die Lage der Störungen usw. angibt. Ein weiteres Nebenkärtchen dient der Darstellung der Grundlagen (Bohrpunkte, Bohrfelder, Aufschlüsse, usw.), die der Darstellung als Unterlage gedient haben.

Profilkarten geben für jeden Punkt des bearbeiteten Gebietes eine Voraussage über die zu erwartende Schichtenfolge und ihre Wasserführung. Infolgedessen ist bei jeder neuen Bohrung die Zuverlässigkeit des Kartenwerkes leicht nachprüfbar. Aus diesem Grund muß die Bearbeitung sehr sorgfältig und gewissenhaft erfolgen, wenn sie sich in der Praxis bewähren soll. Die bisherigen Erfahrungen im praktischen Gebrauch des Kartenwerkes sind zufriedenstellend gewesen.

LITERATUR

BREDDIN, HANS: Ein neuartiges hydrogeologisches Kartenwerk für die südliche Niederrheinische Bucht. — *Zeitschr. deutsch. geol. Ges.*, 106, (1954), S. 94-112, Tafel 1, Hannover 1956.

CARTES ET BLOCDIAGRAMMES DES EAUX SOUTERRAINES

ERNST SOBOTHA

Construisant des cartes hydrogéologiques l'auteur présenta en 1937 dans le « Zeitschrift Deutsch. Geol. Ges. » et 1941 dans le « Zs. f. prakt. Geologie » des méthodes d'une claire classification des observations. C'était une carte avec des courbes de niveaux contenant l'émergence des sources et des puits qui correspondait avec une carte géologique contenant les dates chimiques des eaux souterraines. La dureté servait de règle, des signes spéciaux remarquaient les chlorures et la température suivant le besoin.

La classification des données faisait construire des cartes démonstrant par des flèches différentes la direction, l'étage et la constitution chimique et à peu près l'émergence des courants souterrains. Des difficultés spéciales furent résolues construisant une série de blocdiagrammes.

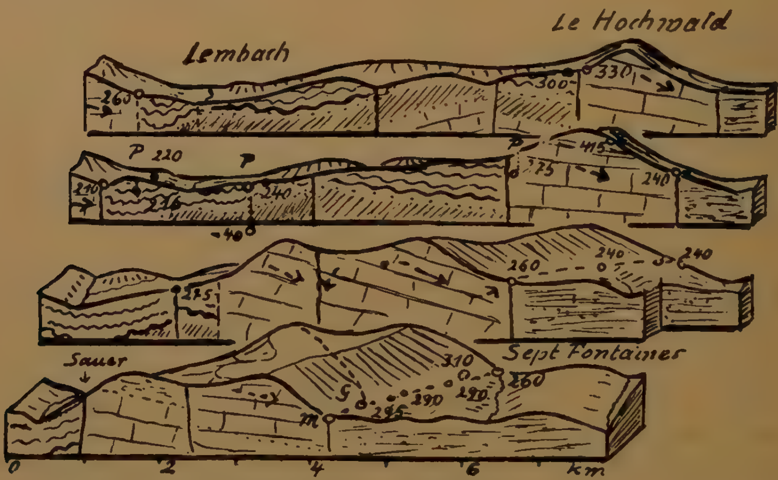


Fig. 1 — Les eaux souterraines autour du HOCHWALD
O: eaux douces ● : eaux dures —> : courants ..... : puits et sondages /et - - - : failles M : Marienbronn G : Großenbronn.

La perfection des séries de blocdiagrammes soit démonstrée remettant les recherches des eaux souterraines autour du *Hochwald*. Les « Horst » du Grès bigarré (Buntsandstein) renferment des eaux douces émergeant surtout suivant les grandes failles. C'est le blocdiagramme qui les met clairement sous les yeux. On y voit un étage supérieur près des sommets et les eaux dures du Muschelkalk. Les chiffres donnent le niveau des sources et l'hauteur de l'eau des puits ou des sondages.

La deuxième série de blocdiagrammes fait voire les oscillations de l'eau souterraine dans des calcaires siluriens. On y voit aussi un étage supérieur effectué par des limons glacials.

La largeur des blocdiagrammes est variable suivant la densité des sources et des puits, la direction doit correspondre avec la structure géologique.

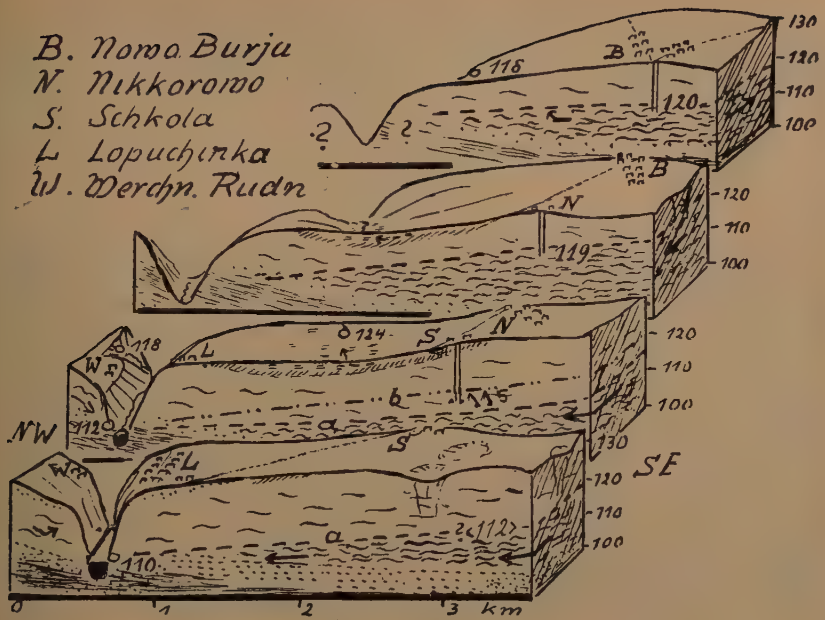


Fig. 2 — Les eaux souterraines au sud-est de Lopuchinka
b : niveau de l'eau souterraine au princtemps *a* : niveau en hiver σ : sources.

DIE PUNKTFÖRMIGE DARSTELLUNG DER REGIONALEN GRUNDWASSER-BESCHAFFENHEIT DURCH EINFUEHRUNG DER MITTLEREN KENNZAHL

FRIEDRICH NÖTHLICH
Hamburg

Im Wirtschaftsleben der Länder hat das Wasser von jeher eine besondere Rolle gespielt. In den Industriebetrieben muß in immer steigendem Maße auf die Nutzung der unterirdischen Grundwasservorräte für die Wasserversorgung zurückgegriffen werden. Die Erkenntnis, daß das Grundwasser für die Ansiedlung und wirtschaftliche Entwicklung ein unentbehrlicher Rohstoff ist, hat dazu geführt, daß die Grundwasservorräte durch immer neue Flach-oder Tiefbrunnen genutzt werden. Bereits im letzten Jahrzehnt ist eine sprunghafte Entwicklung derjenigen Wirtschaftszweige zu verzeichnen gewesen, die sich durch den Bau von Vertikal-, Horizontal-oder Diagonal-Brunnen unabhängig von jeder zentralen Wasserversorgung gemacht haben.

Um zuverlässige Unterlagen über Menge und Beschaffenheit des Grundwassers zu haben, wurden in den letzten Jahrzehnten systematisch zahlreiche Aufschlußbohrungen und Pumpversuche aus Brunnen durchgeführt. Karten, die die Eigenschaften des Grundwassers ausweisen, konnten aber bisher nur in den Ländern angefertigt und benutzt werden, die über genügend Untersuchungen und eine auf den Verwendungszweck abgestellte Darstellungsmethode verfügten.

Für die Bearbeitung eines umfangreichen Analysenmaterials über die Grundwasser-Eigenschaften wird ein Verfahren vorgeschlagen, das gestattet, die auf Lochkarten gebrachten Analysenwerte unter Verwendung eines Bewertungsschemas punktförmig darzustellen. Die Einteilung und Bewertung läßt sich beim unterirdischen Wasser wesentlich einfacher durchführen, da bestimmte Einflüsse, wie sie z.B. beim oberirdischen Wasser vorkommen und wirksam werden, nicht in dem Maße in Erscheinung treten und bei tieferen, durch Deckschichten abgeriegelten Grundwasser-Vorkommen sogar ausgeschlossen sind. Die eingeführten Bewertungszahlen

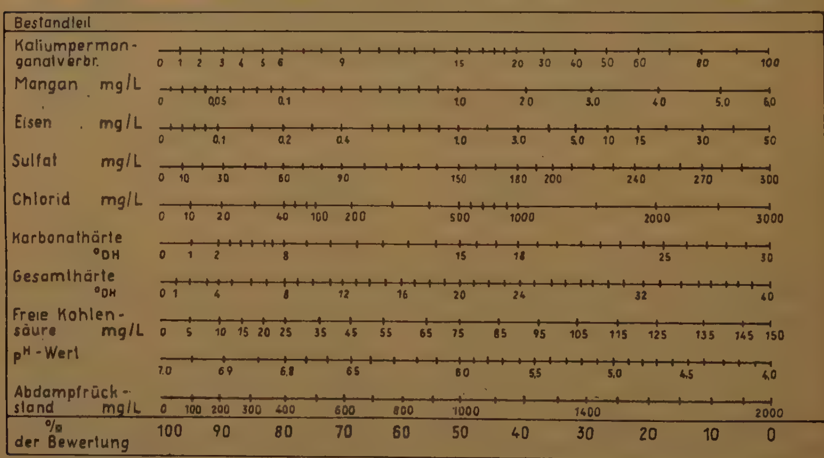


Abb. 1 — Bewertungsschema zur Ermittlung der Bewertungszahl in Prozenten der Grundwasserbeschaffenheit unter Berücksichtigung des Verwendungszweckes.

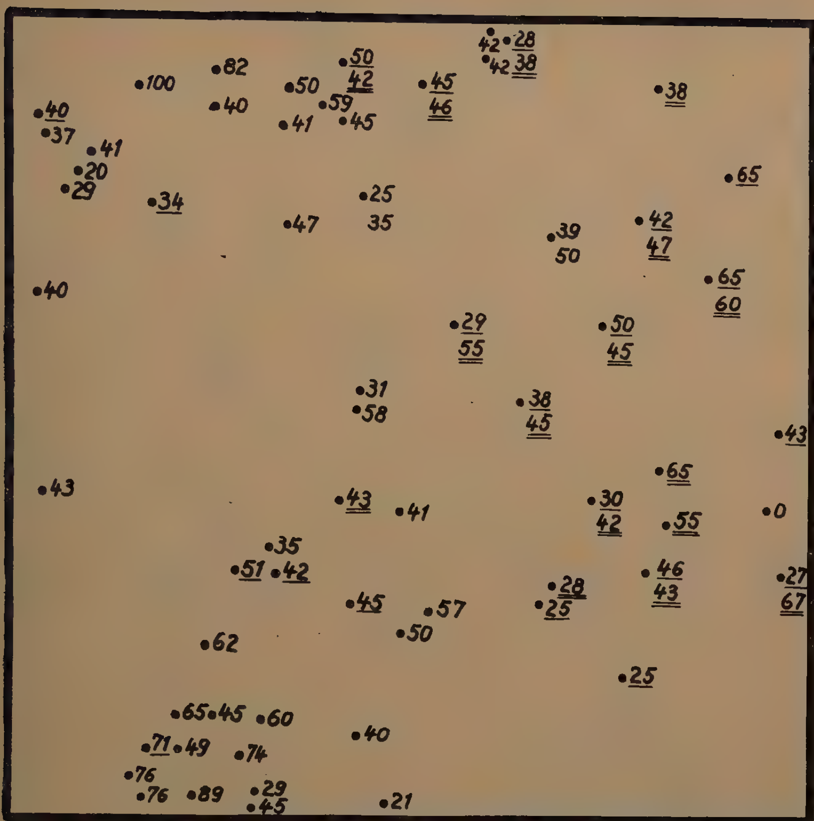


Abb. 2 — Kartenmuster. Bewertungszahlen für die Gehalte an Eisen. Die Zahl der Striche unter den Zahlen dient zur Unterscheidung verschiedener Grundwasserstockwerke (Kein Strich : Oberes Grundwasser, 1 Strich : 1. Grundwasserleiter, 2 Striche : 2. Grundwasserleiter, 3 Striche : 3. Grundwasserleiter).

für die vorkommenden chemischen Bestandteile im Grundwasser sind bei der Aufstellung dieses Bewertungsschemas benutzt worden (Abb. 1). Um jeden Bestandteil der Analyse festlegen zu können, bedurfte es der Aufstellung von Grenz-oder sog. Richtzahlen, denen Bewertungszahlen zugeordnet sind. Diese Bewertungszahlen sind nicht willkürlich gewählt, sondern auf Grund bisher vorliegender Erfahrungen und Mitteilungen über die betriebliche Verwendbarkeit des Grundwassers für Trink- oder Brauchwasserzwecke entnommen.

Mit der Bewertung 100 % ist die Eigenschaft des Grundwassers belegt, die die Verwendung des Grundwassers ohne Aufbereitung möglich macht.

Die Abstufung auf 90 % bis 80 % ist eingeführt worden, um geringe Gehalte an Eisen, Mangan oder Erdalkalien anzuzeigen, die für industrielle Zwecke der Wasserversorgung von Bedeutung sind.

Zwischen 80 % und 50 % in der Bewertung liegen die Gehalte derjenigen chemischen Bestandteile, die eine Aufbereitung des Grundwassers erfordern.

Von 50 % bis 0 % ist es schwierig, das Grundwasser aufzubereiten. Die Grenze der wirtschaftlichen Tragbarkeit wird überschritten.

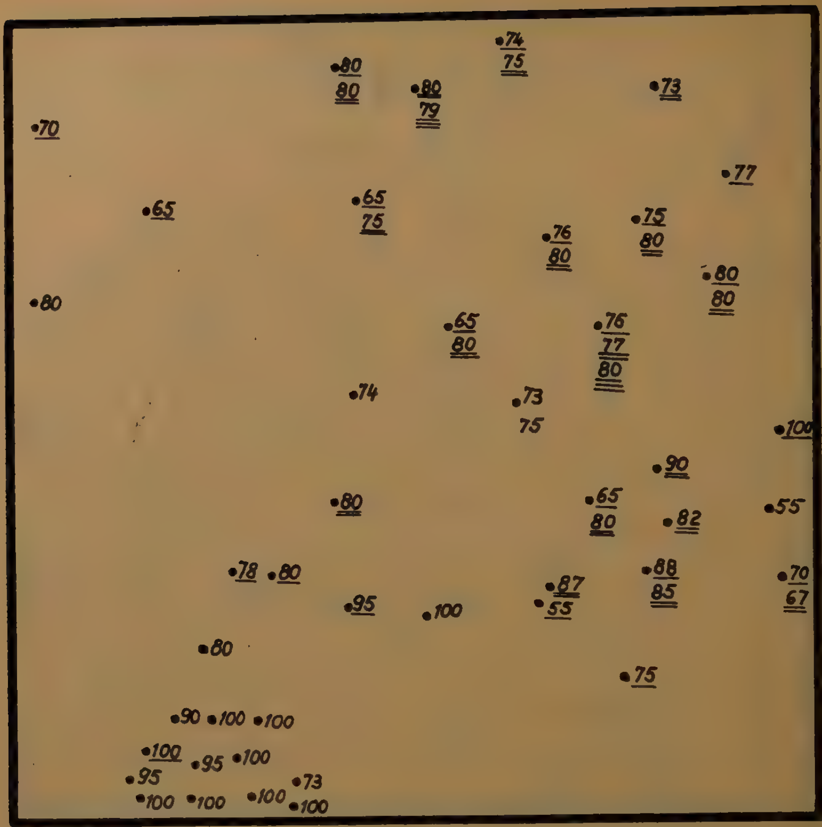


Abb. 3 — Kartenmuster. Bewertungszahlen für die Gehalte an Mangan.

Benutzt man diese Bewertungstabelle und ermittelt daraus für die einzelnen chemischen Bestandteile die jeweiligen Bewertungszahlen, so hat man die für die praktische Arbeit erforderlichen Unterlagen. Alle Einzelwerte kann man zur besseren Übersicht kartographisch in punktförmiger Darstellung wiedergeben. Jede Meßstelle braucht nur durch eine Zahl gekennzeichnet zu werden (Abb. 2-5). Die Schwierigkeiten einer farbigen Wiedergabe oder der Kennzeichnung durch Signaturen werden vermieden. Mittelt man die Einzelwerte einer bewerteten Analyse, so erhält man eine mittlere Kennzahl, die mit anderen Kennzahlen vergleichbar ist. Dabei ist es zweckmäßig, jede mittlere Kennzahl mit einem Index zu versehen, der von links nach rechts die benutzte

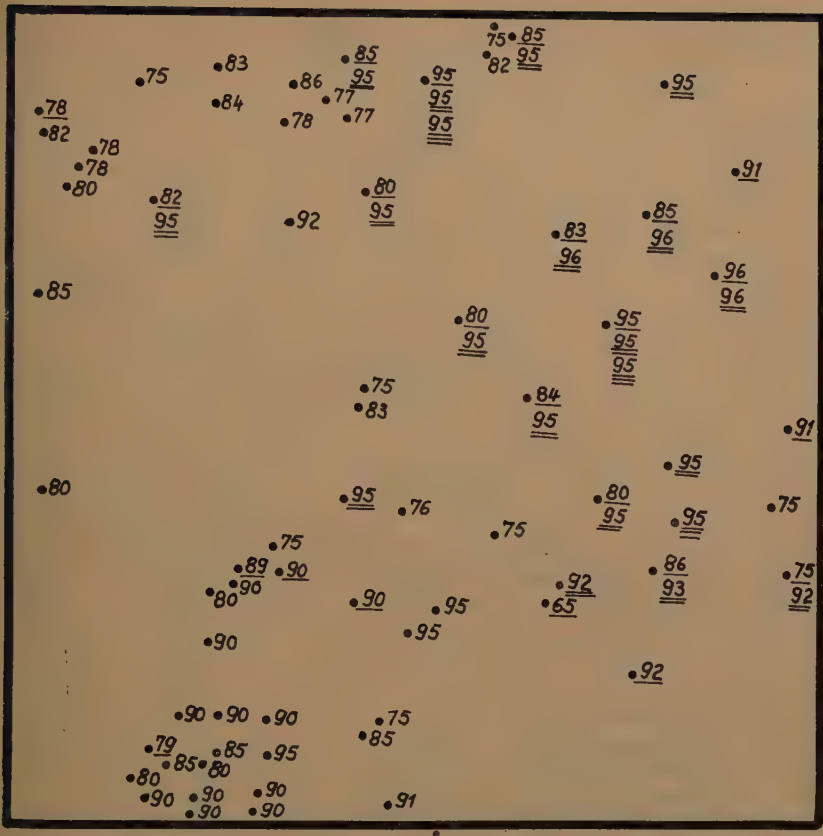


Abb. 4 — Kartenmuster. Bewertungszahlen für die Gehalte an Chloriden.

Anzahl der chemischen Bestandteile und diejenigen Bewertungszahlen angibt, die unter einer als Norm festgesetzten Bewertungszahl liegen (Abb. 6). Dadurch erreicht man, daß das Auftreten mehr oder weniger hoher Gehalte einzelner chemischer Eigenschaften kenntlich gemacht wird. Für die praktische Verwertung bieten sich Vorteile, indem aus einer Übersichtskarte die regionale Beschaffeneit des Grundwassers beurteilt werden kann. Eine abschließende Begutachtung über die Verwendbarkeit einer Grundwasserart kann und soll die Darstellung der mittleren Kennzahl nicht vermitteln. Bei der Planung und Ausweisung von Industriegelände mit Brauchwasser-Versorgung hat sie ihre Berechtigung.

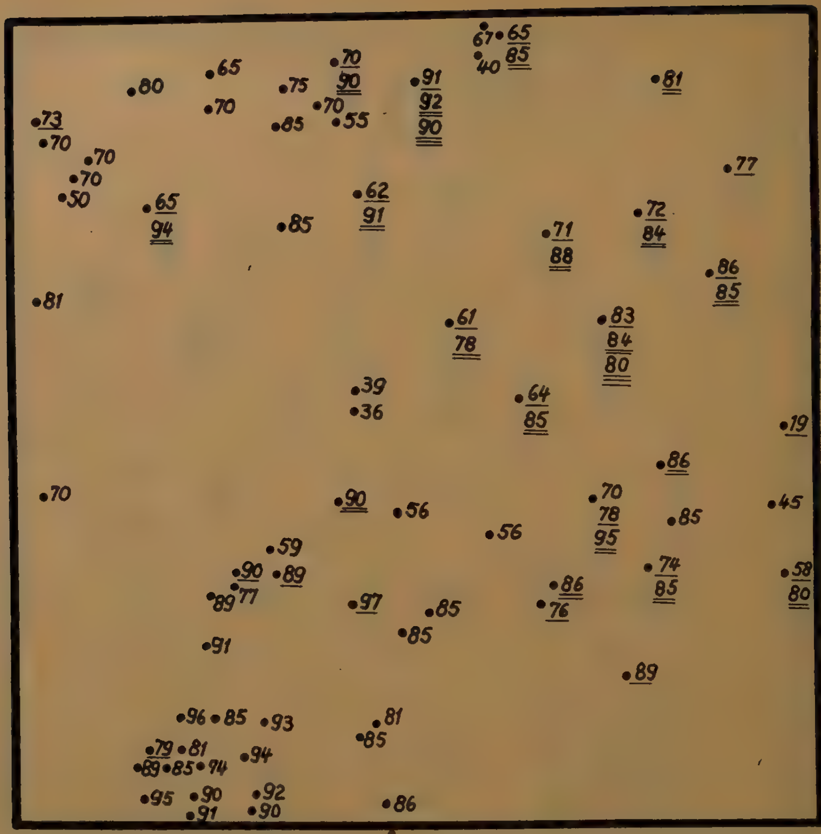


Abb. 5 — Kartenmuster. Bewertungszahlen für die Gesamthärte.

Dieses Verfahren erleichtert die Übertragung auf ein geeignetes Lochkartenschema und ermöglicht dadurch nicht nur eine schnelle Auswertung durch stufenweise Auslesung, sondern auch eine Sortierung derjenigen Meßstellen, die entsprechende oder günstige Verwendungsmöglichkeiten des Grundwassers aufweisen. Ein umfangreiches Material kann den Anforderungen entsprechend nach allen Gesichtspunkten untersucht und gebietsweise zusammengestellt werden.

Mit dieser Darstellungsart wird versucht, ausschließlich den Verwendungszweck vor der Grundwasser-Erschließung in den Vordergrund zu stellen, da bei jeder Raumplanung und Ausweisung von Flächen die Wasserversorgung eine nicht unwesentliche Rolle spielt. Die wirtschaftliche Entwicklung und Industrialisierung werden es mit sich bringen, daß in den nächsten Jahren eine zweckentsprechende Standortwahl unter Berücksichtigung der Wassergewinnungsmöglichkeiten durch Eigenwasser-Versorgungen getroffen werden mussen.

Abb. 6 — Kartenmuster. Mittlere Kennzahlen der Grundwasser-Beschaffenheit.

LITERATUR

NÖTHLICH, F. : Die Darstellung der regionalen Grundwasserbeschaffenheit durch Einführung der mittleren Kennzahl. — *Wasser und Boden*, 5, S. 253-255, Hamburg 1953.

EXEMPLE D'UNE CARTE HYDROGEOLOGIQUE POUR UN BUT SPECIFIQUE

A. VOLKER
Service pour l'aménagement des eaux
La Haye - Hollande

RÉSUMÉ

Les cartes hydrogéologiques usuelles donnent des renseignements de caractère général sur les conditions des eaux souterraines et sur la constitution géotechnique du sous-sol. Il est souvent très difficile de représenter toutes les données par une seule carte. Pour remédier à cet inconvénient, on peut se servir de profils dans lesquels on peut représenter beaucoup plus de données que dans une seule carte.

Quelque soit le système de cartographie adopté il restera toujours à dresser des cartes hydrogéologiques spéciales lorsqu'il s'agit de résoudre un problème géohydrologique bien défini. Le caractère de ces cartes est déterminé par le problème pratique qui se pose et par les conditions spécifiques du terrain.

La communication donna un exemple d'une telle carte — ou plutôt d'une série de cartes — ayant pour but de trouver pour un terrain étendu la résistance de couches semi-perméables et la variation locale de ces résistances. Pour résoudre ce problème, il fallait disposer de cartes hydrologiques se rapportant aux vitesses de remontée des eaux souterraines et aux surpressions (différence de hauteur entre le niveau piézométrique des eaux souterraines en dessous des couches semi-perméables et le niveau phréatique).

Dans leur communication (Some remarks on hydrogeological mapping in the Netherlands) MM. Zonneveld et Beltman soulignent les difficultés qui se présentent losqu'on veut représenter dans une seule carte toutes les données hydrogéologiques désirées. Aussi les auteurs proposent de se servir d'une série de cartes et de profils pour faire ressortir d'une façon suffisamment claire les diverses données.

Par un tel procédé l'on dispose d'un grand nombre de possibilités. Toutefois, les cartes hydrogéologiques se borneront toujours à des données de caractère général donnant un premier aperçu des conditions hydrogéologiques de la région. Pour des qroblèmes spécifiques, il faudra bien souvent exécuter des recherches complémentaires dont les résultats peuvent également être représentés par des cartes. Le caractère de celles-ci sera bien différent des cartes hydrogéologiques ; il sera déterminé par le problème spécifique qui se pose, et par les conditions spéciales de la région.

Dans la présente communication nous donnerons l'exemple d'une carte dressée afin de fournir les données de base nécessaires pour résoudre un problème particulier.

Le problème est celui du rabattement de la nappe phréatique dans la périphérie des polders asséchés dans l'ancien golfe du Zuiderzee (transformé en Lac de l'IJssel). La création de ces polders demande en effet un abaissement du plan d'eau par pompage, de 4 ou 5 mètres pour permettre la mise à sec du fond. La différence de niveau ainsi créée entre le nouveau terrain et les régions adjacentes donne lieu à une infiltration souterraine, infiltration qui dépend, outre cette différence de niveau, de la constitution géologique.

Dans le cas présent il s'agit de l'influence de l'asséchement du Polder Flevoland sur la région côtière du « Veluwe ». (*fig. 1*).

Le « Veluwe » est une vaste région sablonneuse d'origine glaciaire présentant des altitudes assez élevées. Par l'absence d'un écoulement superficiel des eaux, une partie de la pluie tombant sur cette région s'infiltre dans le sous-sol (325 mm par an sur une pluviosité de 750 mm) et approvisionne un réservoir souterrain d'eau

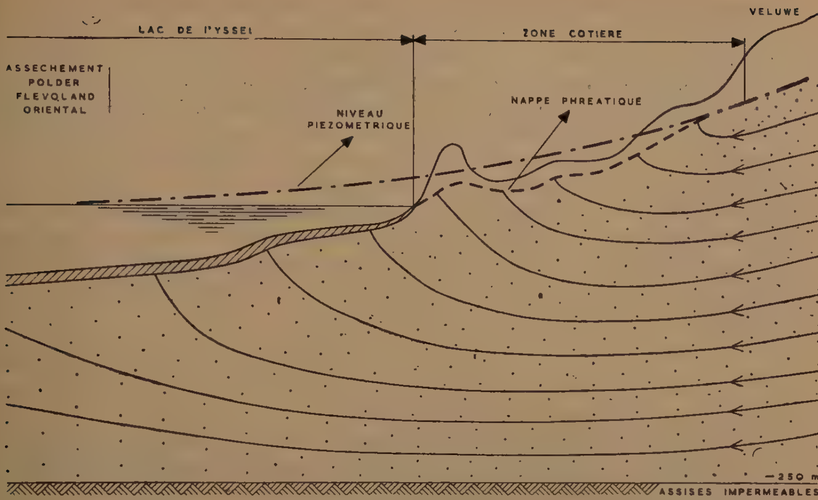


Fig. 1 — Remontée des eaux souterraines dans la zone côtière du Veluwe.

douce. Les eaux en excédent s'écoulent sous forme de courants souterrains orientés en toutes directions. Le courant d'eau en direction du lac, c'est à dire en direction nord-ouest, se transforme en partie en eau de surface dans la zone côtière du Veluwe. Cette zone à une altitude relativement basse, se distingue du Veluwe par la présence de couches sémi-perméables à la surface constituées par des argiles et des tourbes. On y trouve des prairies et des terres labourables. Le sous-sol est constitué par des sables perméables (k = 30 m par jour) reposant sur des assises imperméables à une profondeur de 250 mètres.

C'est la remontée des eaux souterraines provenant du Veluwe qui maintient le niveau de la nappe phréatique dans cette zone (fig. 1); sans cette alimentation en eau douce la zone cotière souffrirait de la sécheresse. Des ruisseaux qui prennent leur origine au pied des collines du Veluwe conduisent les eaux en excédent vers le lac. Le reste du courant souterrain passe en dessous de la ligne côtière et remonte dans les couches de fond du lac, où une poussée des eaux souterraines a pu être observée jusqu'à une douzaine de kilomètres de la côte.

L'asséchement du Polder Flevoland pourra modifier ce régime de telle façon que les eaux souterraines du Veluwe, attirées par le nouveau polder à basse altitude, cesseront d'alimenter la zone côtière par leur apport d'eau. Il importe donc de pouvoir donner une prévision de l'abaissement éventuel de la nappe phréatique dans cette zone.

Cette prévision demande une connaissance de plusieurs facteurs géotechniques qui se rapportent à la zone côtière proprement dite et aux périfériques. Nous avons parlé de ce problème dans un rapport antérieur [1]); ici nous nous bornerons à la détermination d'un de ces facteurs par l'emploi de cartes hydrogéologiques.

Le facteur géotechnique en question est celui de résistance c des couches superficielles dans la zone côtière contre la remontée des eaux souterraines dans cette zone. Les couches superficielles ne sont pas homogènes et leur résistance à l'infiltration

([1]) Conséquences hydrologiques de l'abaissement artificiel du plan d'eau dans un polder à assécher pour les régions périphèriques. (Congrès de l'U.G.G.I. Rome 1954).

des eaux diffère d'un endroit à l'autre. En outre il se présente parfois dans le sous-sol à de faibles profondeurs d'autres couches sémi-perméables qui offrent également une certaine résistance contre le passage des eaux.

1. Conséquences hydrologiques de l'abaissement artificiel du plan d'eau dans un polder à assécher pour les régions périphériques (Congrès de l'U.G.G.I.-Rome 1954)

Par suite de la constitution des couches sémiperméables, la remontée des eaux souterraines est plus ou moins diffuse. Les eaux qui ont atteint la surface sont collectées dans des fossés qui débouchent dans les ruisseaux, dont le débit — par un temps sec — augmente progressivement du pied des collines vers la côte. Les eaux dans le sous-sol sont donc dans un certain sens des eaux artésiennes : le niveau piézométrique est en effet supérieur au niveau de la nappe phréatique.

D'après la loi de Darey, la remontée des eaux souterraines est déterminée par la formule

$$v = k^1 \frac{p}{d} = \frac{p}{c} \qquad (1)$$

où

v = vitesse moyenne de la remontée des eaux en mètres par jour

p = différence en mètres du niveau piézométrique et du niveau de la nappe phréatique (appelée « surpression »),

d = épaisseur en mètres des couches sémi-perméables.

k^1 = coefficient de perméabilité moyenne en mètres par jour.

$c = \frac{d}{k'}$, résistance (exprimée en jours) des couches semi-perméables.

En principe on pourrait calculer la résistance c par la connaissance de k^1 et de d, cette dernière valeur étant connue par les résultats des forages. Or la détermination, de k^1 présente des difficultés spéciales.

On ne saurait en effet déterminer le facteur k^1 par des essais sur des échantillons étant donné que la perméabilité moyenne des couches semi-perméables dépend beaucoup plus de la présence et de l'étendue des inhomogénités présentes dans ces couches, que de la perméabilité de la matière presque imperméable proprement dite.

Le seul moyen possible de déterminer la valeur de c se trouve dans la formule (1) qui indique que cette valeur donne le rapport entre la vitesse de remontée des eaux souterraines et la surpression.

L'on doit donc disposer des cartes hydrogéologiques suivantes :

a. Une carte représentant les vitesses de remontée des eaux souterraines pour les diverses parties de la zone considérée.

b. Une carte donnant les niveaux de la nappe phréatique dans la zone, niveaux qui peuvent varier d'un endroit à l'autre.

c. Une carte analogue pour les niveaux piézométriques des eaux dans le paquet perméable

d. Une carte donnant les surpressions, cette carte peut être déduite immédiatement des cartes b etc.

a. L'élaboration de cette carte demande des mesurages prolongés des débits des ruisseaux qui s'écoulent dans la zone côtière. En dressant des bilans d'eau pour les divers bassins versants, on peut calculer la partie du débit de ces cours d'eau qui est due à l'apport par les eaux souterraines. Pour éliminer tant que possible les effets de l'évaporation et de la rétention, les bilans sont dressés pour la période décembre-février, alors que l'évaporation est faible et que la nappe phréatique ne varie que très peu. On dispose ainsi de données assez précises sur les moyennes des

vitesses pour un nombre de bassins versants. Par des mesurages de débit intermédiaires dans les affluents des ruisseaux, l'on peut trouver la distribution plus détaillée de ces vitesses dans l'aire de chaque bassin versant.

C'est ainsi que les lignes donnant les vitesses de la remontée des eaux souterraines pour chaque endroit de la zone côtière ont été conçues (*fig. 2*). Le maximum

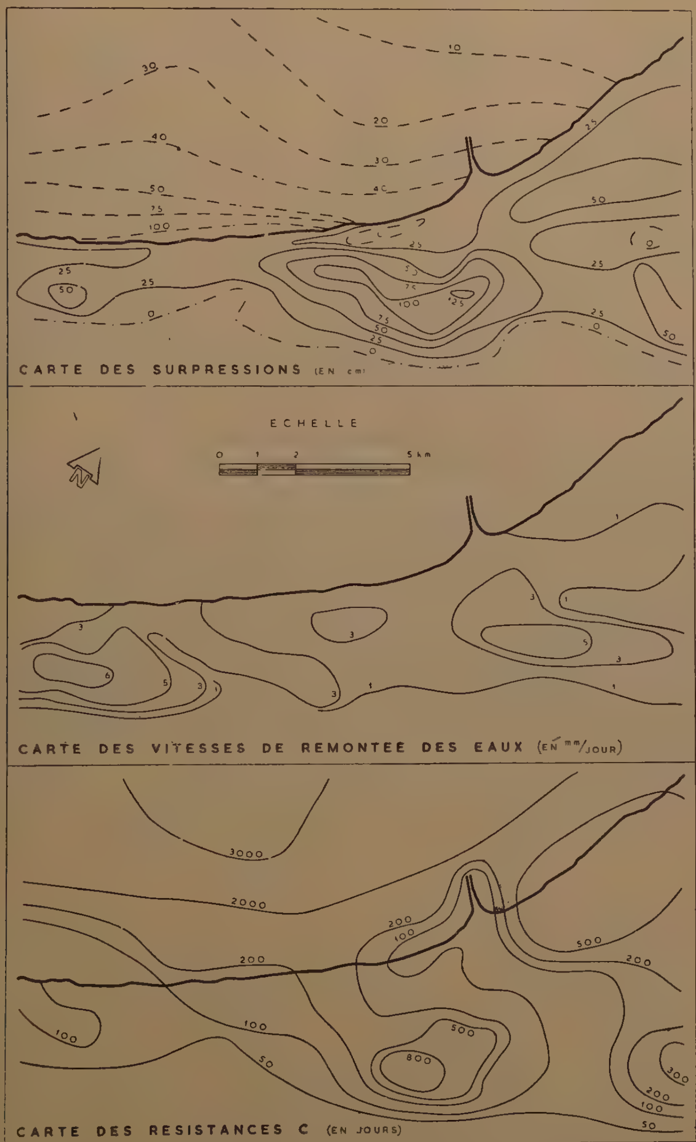


Fig. 2 — Cartes hydrogéologiques de la remontée diffuse des eaux souterraines dans la zone côtière du Veluwe.

qui se présente est de 6 mm par jour; les vitesses diminuent en direction du pied des collines.

b. Les niveaux de la nappe phréatique ont été trouvés par des observations dans une centaine de tubes à filtre enfoncés jusqu'à une telle profondeur que la nappe phréatique a été atteinte tout juste. Sous l'effet de la remontée permanente des eaux souterraines, cette nappe ne présente que de faibles oscillations saisonnières.

c. Les niveaux piézométriques des eaux souterraines à grandes profondeurs ont été observés à l'aide de quelques dizaines de tubes à filtre enfoncés par sondage à percussion jusqu'à une profondeur de 25 mètres au moins. En général les couches semi-perméables dont la résistance *c* doit être trouvée, se trouvent bien au-dessus de ce niveau. Les niveaux observés se rapportent donc au niveau piézométrique dans tout le paquet perméable. Pour vérifier encore ce point de départ, quelques sondages ont été poussés jusqu'à du des profondeurs de 100 et de 300 mètres atteignant donc les assises du paquet perméable. Comme les niveaux piézométriques varient beaucoup plus régulièrement d'un endroit à l'autre que les niveaux de la nappe phréatique, il est possible de limiter le nombre des tubes à filtre à quelques dizaines.

d. La différence de hauteur entre les niveaux mentionnés sous *c* et *b* donne supression des eaux souterraines pour chaque endroit. La fig. présente la distribution de ces surpressions dans la zone considérée. La maximum est de 1,25 m; à cet endroit il se présente des eaux artésiennes dans le sens propre du mot.

Par simple division des surpressions (en mètres) et des vitesses de remontée (en mètres par jour), l'on trouve enfin les valeurs de la résistance *c* (en jours) pour chaque point de la zone (fig. 2).

Ces valeurs varient considérablement d'un endroit à l'autre suivant l'épaisseur et le degré d'homogénité des couches superficielles. Dans la zone côtière les valeurs les plus élevées (jusqu'à 800 jours) doivent être attribuées à la présence de couches semi-perméables dans le sous-sol à une profondeur de 15 mètres à peu près.

Dans le Lac de l'IJssel, à quelques kilomètres de la ligne côtière, l'on trouve des résistances encore plus grandes : ici les couches superficielles n'ont pas été perforées par les ruisseaux et les fossés comme dans la zone côtière. Pour la partie dans le lac les suppressions ont été également déterminées par l'observation des niveaux piézométriques par rapport au niveau d'eau du lac; les vitesses de remontée des eaux ont été déterminées par l'observation des teneurs en sel des eaux dans les couches de fond du lac.

TYPES OF HYDROCHEMICAL MAPS IN HYDROGEOLOGY

A. I. SILIN-BEKCHURIN

1. Hydrochemical maps are compiled for every aquifer and for a water saturated mass of rock including a series of aquifers.

2. In compiling hydrochemical maps the underground waters divided into: fresh (with mineralization of less than 1 gr. per litre), slightly saltish (1—3 gr per litre), saltish (3—10 gr per litre), saline (10—50 gr per litre), brines (50—350 gr per litre). Some other gradations are assumed depending on the aim of a hydrochemical map.

3. As regards their chemical composition the underground waters are divided into: hydrocarbonate, sulphate, chloride and intermediate types of waters. Waters of homogeneous composition are united into hydrochemical zones.

4. As regards their chemical and gaseous composition the underground waters are divided into zones of carbon dioxide, hydrogen sulphite, nitrogen and mixed types of waters. On regional hydrochemical maps of vast territories these zones are united into hydrochemical provinces, for example, a map of mineral waters of the USSR (A. I. Dzens-Litovsky and N. I. Tolstikhin) which shows three provinces on the territory of the USSR. They are as follows: 1) the province of mineral waters evolving carbon dioxide, 2) the province of thermal waters evolving nitrogen of methane, 3) the province of highly mineral waters faintly evolving nitrogen or methane. Besides, there are regions of underground waters in the weathering crust with prevalent fresh waters, and mineral wells.

5. In compiling hydrochemical maps illustrating the chemical composition of several aquifers successive in their depth, there are three methods to be used:

a) hydrochemical maps-sections with certain intervals in depth (100; 200; 300 m);

b) maps of thickness of the underground waters hydrochemical types and their surface maps;

c) maps of hydrochemical belts with parts of artesian basins above consisting of one or several hydrochemical zones alternating successively with depth.

CLASSIFICATION OF UNDERGROUND WATERS RESOURCES AND THEIR REFLECTION ON MAPS

N. A. PLOTNIKOV & G. B. BOGOMOLOV

RÉSUMÉ

1. Les eaux souterraines sont les plus importantes parmi des fossiles minéraux utiles dont l'acceptation dans la vie et dans l'activité pratique de l'homme est bien connue. Pour une juste direction des explorations hydrogéologiques, de l'appréciation de l'étude des eaux souterraines, de la projection et de la construction des captages à l'Union Soviétique une classification des réserves des eaux souterraines fut élaborée et aussi s'applique-t-elle pour d'autres minéraux.

D'après le décroissement du degrès de l'étude des réserves des eaux souterraines sont divisées en trois catégories : A, B et C et des subdivisions A_1 et A_2, C_1 et C_2, la catégorie B n'a pas de subdivisions. Chacune des catégories mentionnées des réserves des eaux souterraines se détermine par toute une série des indices caractéristiques propres à l'une ou l'autre catégorie. L'application de la classification des réserves d'eaux souterraines en exploitation est déterminée par une instruction permettant d'apprécier assez nettement les réserves d'eaux souterraines au point de vue de la quantité et de la qualité.

2. A l'application quantitative des eaux souterraines on peut distinguer des aspects suivants des réserves d'eaux souterraines (ou des ressources);

a) le débit du courant souterrain;

b) les réserves régulatrices (le volume d'eau gravitationnelle dans la zone d'agitations des nappes libres des eaux souterraines);

c) les réserves séculaires (le volume d'eau dans l'horizon aquifère avec la nappe libre plus bas de la zone des fluctuations des niveaux et aussi tout le volume des eaux souterraines avec une pression);

d) les réserves en exploitation (le débit qu'on peut obtenir de l'horizon aquifère sur la période à calculer par des constructions des captages rationnels au point de vue économique et technique; notons qu'à cela la qualité d'eau ne doit pas être écartée des conditions admises).

3. Les catégories des réserves d'eaux souterraines classées pour apprécier la perspectivité des régions séparées par rapport à l'utilisation de leurs réserves d'eaux sont montrées sur la maquette de la carte hydrogéologique, cette carte, en outre, donne le moyen d'apprécier les conditions hydrogéologiques des régions où les recherches sur les eaux souterraines pour leur utilisation doivent être poursuivies.

4. L'appréciation qualitative des eaux souterraines on la donne en conformité avec l'utilisation d'après les données des analyses d'eaux, en prenant en considération des facteurs naturels et sanitaires et leur changement sous l'influence des facteurs naturels et artificiels.

Underground waters are widely used for water supply, irrigation, treatment and as raw materials for extracting various components (sodium chloride, iodine, bromine, etc.)

To solve problems of using underground waters it is necessary to be aware of discharge to be obtained in the utilization of the waters with account of their composition. Besides, one must take into consideration a possible change in discharge and composition of underground waters in time,.

To make better hydrogeological investigations, a better estimation of progress in the study of underground waters as well as to solve problems of projecting and constructing catchments a classification of exploited water resources (like other mineral resources) has been worked out and put into practice in the USSR.

Wide-scale investigations of underground waters in the USSR made it possible to reveal their resources and map out ways of their rational utilization. To solve projection and construction problems aimed at the exploitation of underground waters in the USSR their resources are registered by corresponding organisations.

Classification of underground water resources under exploitation gives a condensed characteristic of extent of hydrogeological exploration and study of underground waters forming five categories: C_2, C_1, B, A_2 and A_1 passing from a less studied category to a more studied one. Each category has its own designation.

The below table gives classification of exploited resources of underground waters, extent of their study and prospecting as well as aims of each category.

Classification of underground water resources under exploitation

Resources category	Prospecting and study	Designation (aim) of the category.
1	2	3
C_2	Underground water reserves estimated from geological and hydrogeological factors.	To plan hydrogeological investigations and to ground drillings of prospecting bores for revealing water.
C_1	Resources supposed to be from hydrogeological investigations (a complex geologo-hydrogeological survey) by natural outputs of underground waters, existing watersheds and some prospection pits.	To make a prospective plan of using underground waters. To choose sections of thorough hydrogeological prospecting, to ground drillings of prospecting and experimental bores.
	Probable resources under complex hydro-geolocal conditions (a non-homogenous structure of aquiferous strata, inconstancy of chemical composition and unsteadiness of water yield) discovered from hydro-geological investigations (a complex geologo-hydrogeological survey) and tests of yield and quality of underground waters in separate points.	At a considerable excess of exploitation resources over the wanted amount—to ground projection quotas on the use of underground waters and to drill exploitation bores.
B	Quantitative resources of underground waters determined from preliminary hydrogeological prospecting and general hydrogeological investigations including experimental pumping out and short-period observations of regime of underground waters and springs in the region of a watershed to	To ground projection quotas with a concrete choice ofn watersheds and catchpments sections; At a conside-

	be. Quality of water for definite purposes is not sufficiently studied.	rable excess of the exploitation resources over the wanted amount—for compiling technical projects and capital investment in the construction.
A_2	Underground water resources are determined quantitatively on the basis of thorough prospecting operations, experimental pumping-outs and investigations at a watershed section. Yields of springs determined by systematic regime observations lasting no less than one year and by data of prospecting and experimental operations on the section of the spring catchment. Water quality for a corresponding purpose was studied sufficiently.	To ground technical projects and capital investments in the construction.
A_1	Underground waters resources have been established and studied sufficiently both, quantitatively and qualitatively from data on the utilization.	To plan every-day exploitation of watersheds and their expansion.

Explanations how to use this classification of resources exploited are given in the instruction worked out by the Ministry of Geology of the USSR. This instruction comprises methodical directives to estimate water resources both in quantity and quality of underground waters for various conditions.

Utilized resources of underground waters depend, first of all, on hydrogeological conditions. These resources may be different for different acquifers as well as on different parts of the same acquifer as water abundance and composition of underground waters may vary. In addition, an aquiferous layer and water level may be occurring deeper on one section than on the other. Various water abundance of some parts of aquifers, occurrence depth of aquiferous layers, underground waters levels as well as a change in water quality bring about different technical and economical conditions of obtaining resources exploited and may affect on the amount of these resources.

In connection with this exploited resources of underground waters have to be compared not only for separate aquifers but also for separate parts of aquifers.

A watershed design of underground waters influences on the amount of exploited resources. A watershed of underground waters is meant as a system of catchment structures including a method of water collection (by pumping out or by gravity).

Let us have a ground stream (fig. 1). Underground waters from this stream can be caught by an ideal horizontal watershed (drainage tubes or galleries), placed somewhat lower than the foot of an aquiferous layer (fig. 1a), a non-ideal (suspended) horizontal watershed (fig. 1b), a watershed of ideal wells*) (fig. 1c) or of non-ideal wells. In the case an ideal horizontal watershed (fig. 1a) we can completely or nearly completely catch a ground stream. In other two cases (fig. 1b and c) we can intercept a ground stream but partially as a part of it will get away; it depends, for instance, (for the scheme in fig. 1c) on a distance between bores. This example testifies to the

(*) «Wells» are vertical catchments (drilling or mine wells).

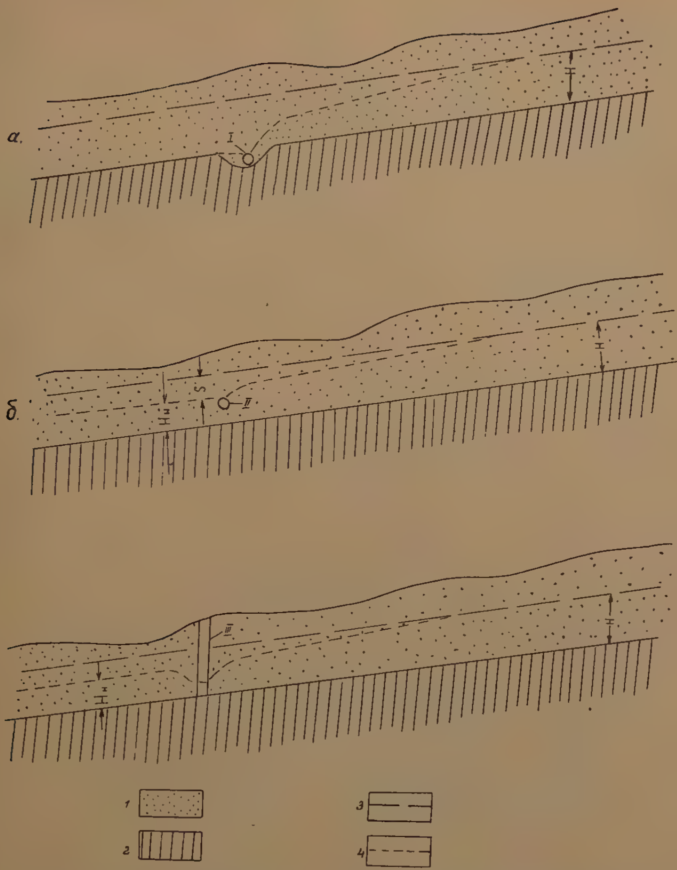


Fig. 1 — Scheme of influence exerted by a watershed design of underground waters on the value of exploitation resources of a ground stream.
a — a latitudinal profile of a ground stream with catching underground waters by an indeal horizontal watershed.
b — the same, but with catching by a suspended horizontal watershed.
c — the same, but with catching by watershed of ideal bores (across the stream).
1 — aquifer.
2 — pressure rocks.
3 — a natural level of ground waters.
4 — level of ground water during their exploitation.
I — an ideal horizontal watershed.
II — a suspended horizontal watershed.
III — a watershed of ideal bores.

fact that amount of exploited resources of underground waters can depend on a watershed design too.

Amount of exploited resources of underground waters is especially affected by hydrogeological conditions. Hydrogeological conditions change in the course of a year of a few years which is, chiefly, determined by nourishment conditions of aquifers. This is accompanied by change in the levels of underground waters, discharge of

underground streams, yields of springs and other hydrogeological indices affecting a change of exploited resources.

Consequently, natural conditions and, chiefly, nourishment of aquifers cause a change in amount of exploited resources.

Analysing problems of underground waters amount we meet the following notions:

1. Water volume in an aquifer (aquiferous zone);
2. Discharge of an underground stream, and
3. Discharge to be obtained from an aquifer by means of catchment structures.

Volume of underground waters is usually expresses in m^3, their discharge—in litre per sec., m^3 p.h., litre per day, m^3 per year. Terms of these notions and combination of these notions while considering amounts of underground waters by different authors are different.

Water volume in an aquifer where we mean water discharge and a lack of saturation is expedient to be divided into two types.

1. *Water volume in a zone of oscillations of underground waters levels with a clear watertable.* This volume varies in the course of a year and a few years, undergoing, for instance, season and perennial oscillations. The above volume controls underground waters discharge, that is why we shall call such a volume of underground waters *control reserves of underground waters.*

2. *Water volume in aquifers with a clear watertable lower than a zone of level oscillations as well as the whole amount of underground waters on sections of pressure aquifers.* Value of this volume of underground waters varies under natural conditions but in a geological time profile, so we call such resources *secular resources.*

It should be noted that under the influence of exploitation and other artificial factors control and secular resources are subject to changes. Besides, it should be borne in mind that under a change of strata pressure secular resources of pressure waters may not change in volume but their mass and weight will be an alternating quantity due to changes of density and volumetrical weight.

Other authors call control and secular resources statical passive and secular resources. However division of underground waters volume into control and secular resources is of theoretical and practical importance. Control resources are an importance element of underground waters balance. The know of control resources often gives possibility of approximately calculate discharge of an underground stream and exploitation reserves of the aquifer.

Discharge of an underground stream is determined by amount of underground water passing through a section (or its part) of the aquifer. This section should be taken as normal to the motion direction of underground waters. On different parts of the aquifer and in different time discharge of an underground stream may be and often is different. The notion «discharge of an underground stream» is often called as dynamical resources, natural dynamical resources and other things by different scientists. However, «discharge of an underground stream» is clear and condensed enough to introduce any new term.

Discharge of underground waters which may be contained from aquifers including springs account being taken of rational technical and economical conditions (design of catchment structures, their location, water hoists, economical indices, etc.) without making harm to exploitation regime and water quality during the period of work of a catchment is now called *exploitation resources of underground waters.*

Infiltration nourishment of underground waters takes place irregularly, in some period of the year whereas in an arid zone even once in a few years. Condensation nourishment of underground waters is significant only in rare cases. If the nourishment of underground waters is regular it gives time for control resources to accumulate

and control the underground run-off. In one of the tapers of Central Asia underground waters nourishment varied during a year from 4.12 m^3 p. sec. to 74.67 m^3 p. sec., i.e. with a coefficient of irregularity 16.7 and runoff from 11.25 to 35.36 m^3 p. sec., i.e. with a coefficient of irregularity — 3.1.

Maximum value of control resources was there 465.5 million m^3. which is approximately 0,62 from the annual run-off. Mapping of control resources on an area of ground waters is effected by a water layer, say in cm., during a whole year or by the maximum value of their accumulation for a certain moment in the course of a year. Fig. 2 shows a model of such a map where control resources are given in cm. of a water layer on the 15th of May 1956.

Secular resources of underground waters are a general index for them and a calculation index for estimating exploitation resources for some cases only, say for estimating underground waters resources of a definite composition (fresh lens among salt ground waters of arid zones, iodine-bromine waters, etc.). Mapping of secular

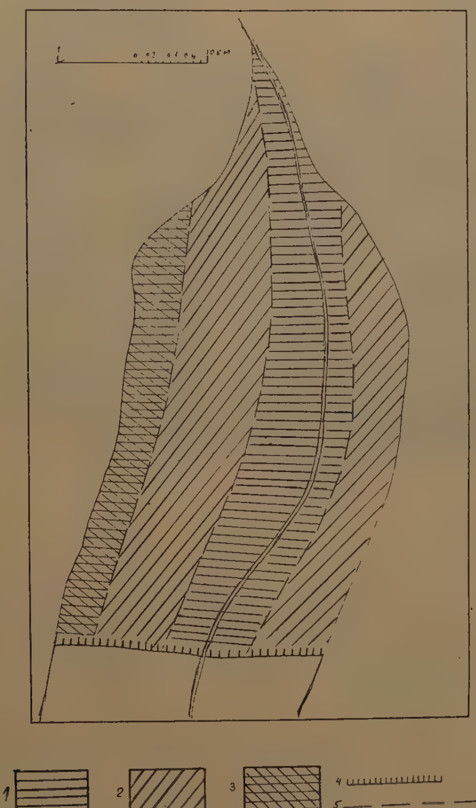


Fig. 2 — Maps of control resources of ground waters in alluvial depositions in the valley.
1 — Control resources on the 15th of May 1956. 100-120 cm of water,
2 — the same at 80-100 cm.
3 — the same at 60-80 cm,
4 — border between ground and pressure waters,
5 — border between specially marked zones of control resources.

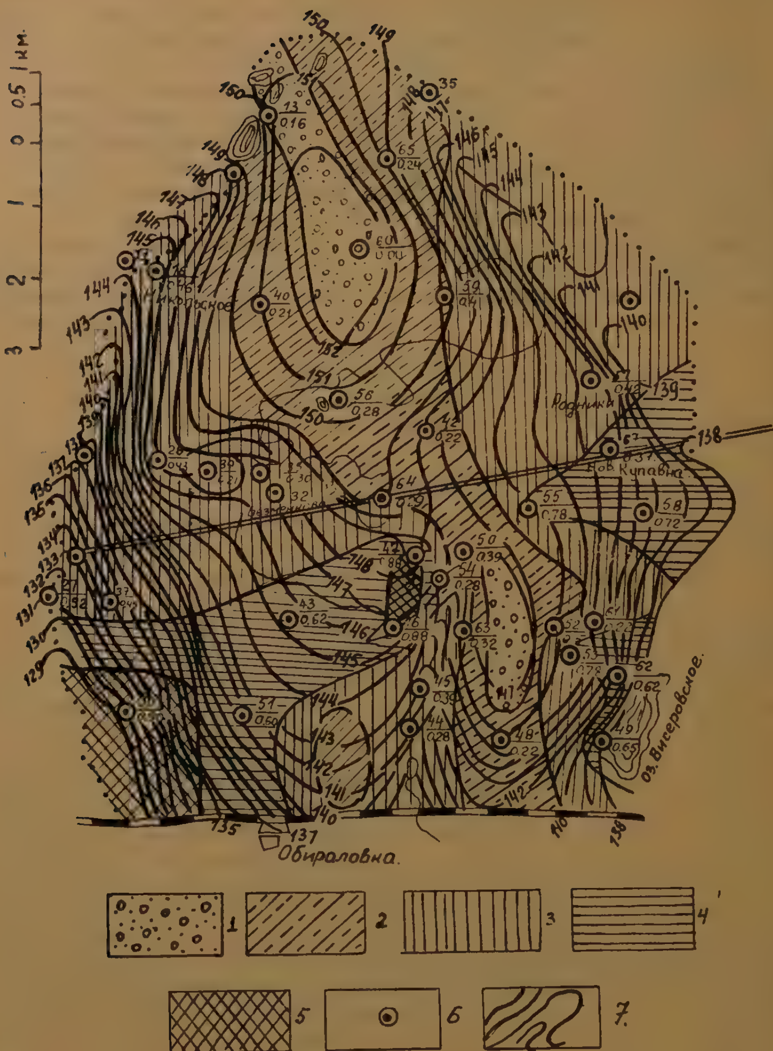


Fig. 3 — Map of discharge of the underground stream per 1 m of ground waters width of left inflows of the Nekhorka River near Moscow (by G. N. Kamensky).

1 — Discharge per 1 m of the stream width form 0 to 0.20 m³ p. day
2 — » » 0.20 to 0.40 »
3 — » » 0.40 to 0.60 »
4 — » » 0.60 to 0.80 »
5 — » » over 0.80 m³ p. day
6 — Drill bore. Figures: top right — the number of the bore, bottom right — discharge value — cm³ per day.
7 — Hydroisogypsia with an interval of 1 m.

resources can effected, as for control resources, in the form of water layer, i.e. quite similarly to the map model in fig. 2.

Discharge of the underground stream, as control resources, characterizes dynamics of underground waters showing renewal of underground water amount. A map in fig. 3 shows plots with different discharge per 1 running meter of a stream width of ground waters. It should be borne in mind, that a change of underground stream value on sections borders is, certainly, gradual and marked borders of these sect ons are only a graphical device. Discharge which may be obtained in the exploitation of underground waters with account for their qualities is called, as it was stated before, exploitation resources. Exploitation resources can be characterized on maps both, qualitatively (in water composition) and quantitatively.

In arid zones ground waters are often salted and occur in salt waters as sections and lens of fresh water. In fig. 4 one can see a distribution of ground waters on an

Fig. 4 — Map of ground water mineralization (by G. N. Kamensky). Value of a dry remainder in gr. p. l.
1 — over 50.
2 — from 10 to 50.
3 — from 2 to 10.
4 — less than 2.

area by mineralization in a valley between the Kura and Araks Rivers. Maps of underground waters mineralization can be compiled in the form of isolines. For underground waters of industrial use as well as for analysis of contents of various elements in waters showing the presence of solid mineral resources there are maps

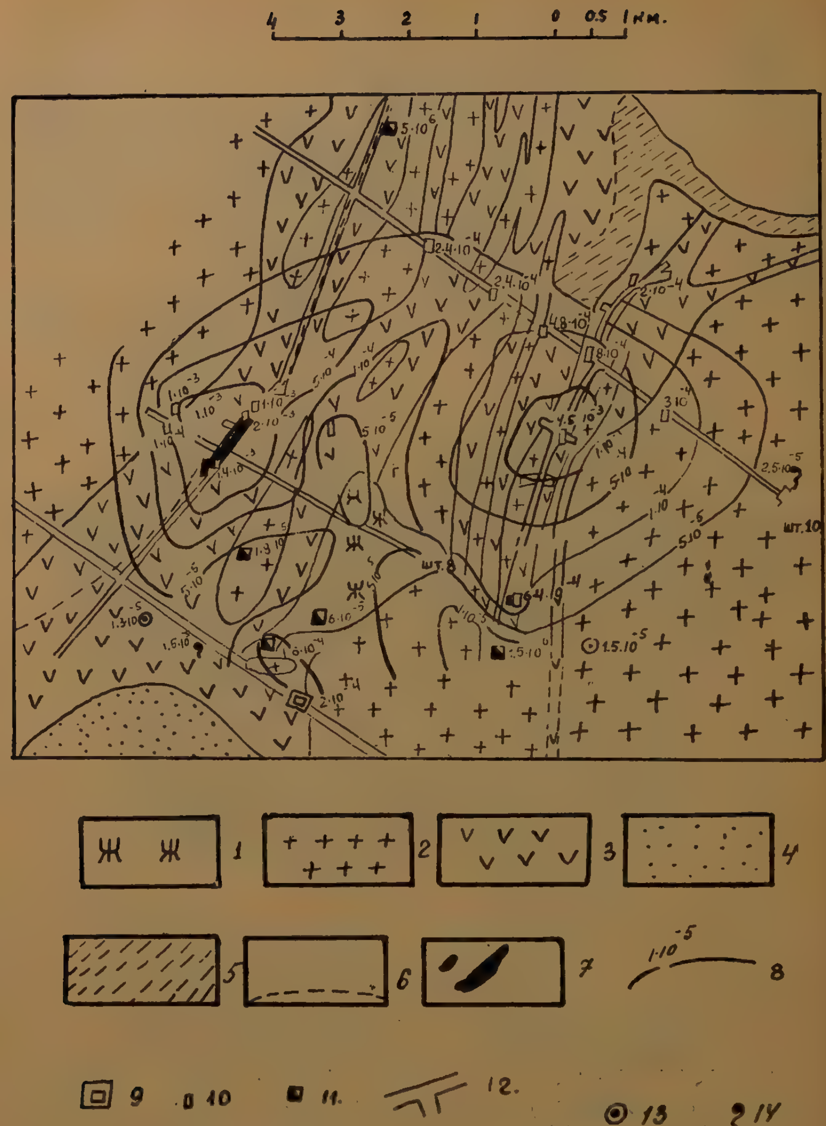
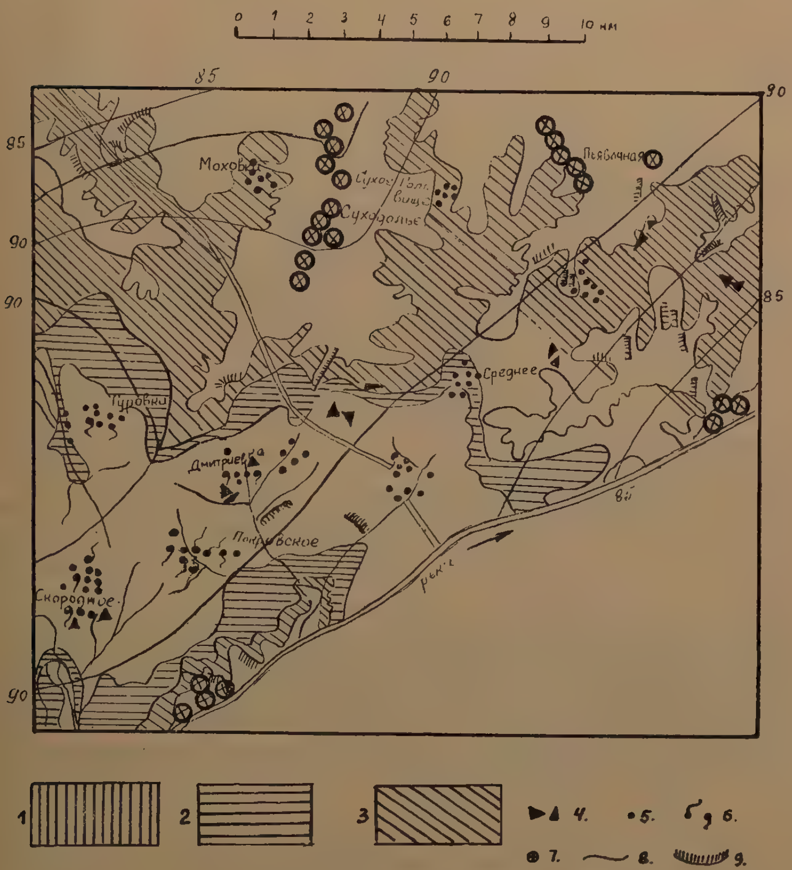


Fig. 5 — Map of isolines showing uranium contents in underground waters (by N. A. Grigoriev).
1 — super depositions «iron cap».
2 — region of total propagation of water abundant horizons,
3 — region of discontinuous propagation of poor-water horizons,
4 — ponds,
5 — wells,
6 — springs of Above-Devonian aquifer,
7 — springs of the Devonian aquifer,
8 — hydroisogypses of the Devonian aquifer,
9 — landslides and traces of bank landslipes.

of such elements contents in underground waters. A map of isolines in fig. 5 shows the contents of uranium in underground waters in gr. per litre. Quantitative characteristics of exploitation resources of underground waters can be different in dependance of hydrogeological conditions and amount of data available as well as on practical value of their utilization.

Area quantitative characteristics of exploitation resources of underground waters with concrete indices is mostly difficult due to insufficient data. In fig. 6 there



is a map of aquiferousity with three grades of water abundance: water abundant aquifers, less water abundant and poor horizons. It is often a case when on the area of water abundant horizons water is wanted for supplying scarcely located collective farms and other poorly populated points. In such cases when water expenses are comparatively small as against water abundance of the horizon (of a few horizons) exploitation resources of underground waters can be expressed as yields of some bores (in litre per sec., m³ p. h.., or better m³ p. day). In fig. 7 there is a map with two areas: one with two artesian horizons, the other — with one, bores yields being written

for each area at the lowering of water level to 10 m. Composition of underground waters, occurrence depths and levels positions can be indicated in appendixes or in other materials.

Fig. 7 — Map of the exploited resources of underground waters in N-region.
1 — areas where bores yields at the lowering of water level down to 10 m are: in sands of the Senonian formation — 10-15 l. p. s., in the marl cretaceous depth of the upper section of the cretaceous system — 5 to 20 l. p. s.
2 — areas where bores yields at the lowering of water level in the Senonian formation are 10-15 l. p. s.
3 — borders of areas with different amounts of exploited resources of underground waters.

In many cases the question is raised to make a maximum use of aquifers all over the whole propagation area, e.g. in the utilization of underground waters for irrigation. In such cases (during irrigation) it should be noted that underground waters are, primarily, used for irrigation during a vegetation period, when exploitation resources of underground waters are expedient to be expressed in the form of annual and dayly discharge taking into account a periodical considerable wear of control resources with their subsequent restoration. On artesian waters areas (in similar cases) when season discharge of exploitation resources takes place a lowering of levels will be greater than during a regular exploitation. In fig. 8 a map of exploitation resources of the artesian horizon for each of the three areas under consideration values of annual discharge which will be caught by a system of bores during an

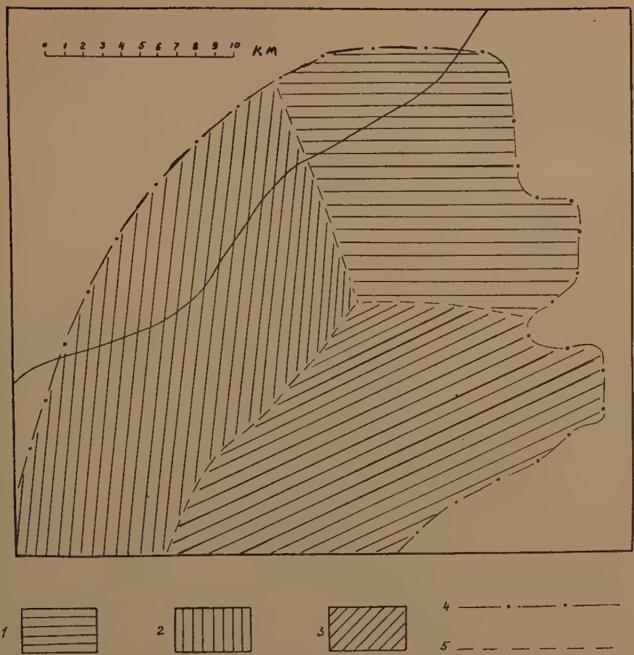


Fig. 8 — Maps of the exploited resources of the artesian horizon.
1 — area where exploited resources of artesian waters are 40 ml m³ p.a.
2 — area where exploited resources of artesian waters are 20 ml m³ p.a.
3 — area with exploited resources of artesian waters 12 ml m³ p.a.
4 — borders of areas with different amounts of exploited resources of artesian waters.

irrigation period. Additional notes and schemes may show occurrence depths of the aquifer, location of bores, of water levels under exploitation, water composition, etc. In dependence on hydrogeological factors, available data and exploitation requirements maps of exploitation resources of underground water can vary. In the present paper problems of classification of exploitation resources have been considered by G. B. Bogomolov, while notions of resources and their mapping by N. A. Plotnikov.

LES CARTES HYDROGÉOLOGIQUES DES RÉGIONS MONTAGNEUSES ET LEUR IMPORTANCE POUR L'ÉVALUATION DES RESSOURCES EN EAUX SOUTERRAINES

A. M. OVCHINNIKOV

professeur à l'Institut de recherches géologiques S. Ordjonikidze de Moscou

Abstract

1. There is a wide variety of hydrogeological conditions in mountain folded regions.

2. From the point of view of hydrogeology the mountain folded regions should be regarded as pressure systems with large fall gradients.

3. The mountain folded regions are characterized by diverse hydrogeological conditions due to their deep partition. They represent small or average-size basins of artesian or ground waters linked with each other, in some places there are larger basins in intermountain hollows. Many basins are of an asymmetrical character and may be treated as artesian slopes.

4. On hydrogeological maps and sections of the mountain folded regions the sizes are given for basins, regions of present infiltration of atmospheric waters,the zone of a run-off or discharge of underground waters. The use of an aerophoto survey permits to take a thorough account of all kinds of aquifering and of a modulus of the underground run-off for different basins in the mountain folded regions. The locating of artesian basins and slopes and plotting them on hydrogeological maps permit to give a quantitative estimate of underground water resources.

5. Hydrogeological maps of the mountain folded regions should indicate all main aquiferous and water-tight complexes (including isolines of their roof), the chief basins and discharge sources. Maps should show the dynamics of fresh waters expressed in hydrocontour lines and hydroisopiezoes.

6. The analysis of the hydrogeological maps for the mountain folded regions shows that higher parts of water permeable massives of rocks constitute not only a region of the modern infiltration of atmospheric waters, but also a region of pressure which is transferred to the whole basin of underground waters and causes a water displacement from closed parts of the structures. Consequently, in zones of discharge foci the observed motion of underground waters is directed to higher massives.

7. A hydrogeological and hydrogeochemical zonal structure of the mountain folded regions caused by oscillations, paleohydrogeological conditions and a level of water permeability of certain complexes is displayed in more complex ways than in platform regions. The inversion of the zones is observed frequently.

8. Within the mountain folded regions are the most valuable deposits of mineral waters, often warm or hot (or overheated sometimes), which are of great importance. The contours of these deposits are shown on the hydrogeological maps. The deposits are included into larger provinces or hydrogeochemical regions, the borders of which must be plotted on hydrogeological maps.

9. The hydrogeological maps are compiled on the basis of geological, tectonic, climatic, geomorphological, hydrological, geobotanical, maps of mineral resources.

10. The accuracy of hydrogeological maps of the mountain folded regions depends on an extent of investigations and prospecting of the regions as well as on the adopted scales. Experience has shown that there should be definite types of map scales:

a) for detailed maps the scale is up to 1 : 10 000 (basin plots and discharge foci are indicated);

b) for maps of separate basins up to 1 : 100 000 (all natural and artificial water outcrops and isolines for the main waterbearing complexes are plotted on the maps);

c) for maps of the mountain folded regions or of the whole region the scale is 1 : 500 000 or 1 : 1 000 000.

d) for general maps illustrating laws of underground waters propagation — less than 1 : 1 000 000.

Les pays montagneux sont des régions d'écoulement intensif superficiel et souterrain où sont répandues de multiples sources; elles diffèrent grandement en cela des régions plates-formes. Ces régions se caractérisent par une grande variété de conditions hydrogéologiques, qui se créent en résultat d'une combinaison complexe de structures géologiques, de relief et de climat. Une importance esentielle ont aussi la position géographique générale du pays montagneux et l'exposition des versants. Nonobstant certains traits communs de morphologie et de structure, les pays montagneux même dans les limites d'une zone unique de plissements diffèrent l'un de l'autre d'une manière assez prononcée au sens hydrogéologique. Par exemple, dans la zone alpine — les Pyrénées ne ressemblent pas aux Alpes; les Alpes différent des Carpathes, ces derniers ne ressemblent en rien au Caucase; le Kopet-dag se distingue apparemment du Pamir, etc. Encore plus importantes sont les particularités hydrogéologiques qui s'observent dans les édifices montagneux des zones de plissements d'âges différents. Des traits hydrogéologiques originaux sont possédés par les montagnes de la Péninsule Scandinave; la remarquable chaîne de montagnes méridionale de l'Oural se détache très distinctement; beaucoup de traits extraordinaires s'observent dans les limites d l'arc énorme de Verkhoiansk-Kolyma, dans les bordures duquel se trouve « le pôle de froid » et, enfin, encore plus complexes sont les édifices montagneux où à notre époque fonctionnent des volcans, des geysers, des fumarolles, des solphatares, etc., par exemple, sur la chaîne de Kamtchatka — îles Kourilles, sur l'Alaska, les îles de Japon, etc.

En relation avec la hydrogéologie, les édifices montagneux doivent être considérés comme des systèmes naturels d'eaux en charge complexes à grands gradients de déclivité d'eaux souterraines; en conséquence de cela il se crée une migration rapide des eaux dans les pores et les fissures des roches; il s'opère un échange d'eau intensif et comme résultat de celui-ci un lavage prononcé des roches.

Avec cela, on ne peut manquer de noter que tous les pays montagneux se caractérisent par une élévation du coefficient d'écoulement, à partir de 0,20 jusqu'à 0,90 au fur et à mesure que l'on s'approche des parties axiales des chaînes de montagnes et que la rapidité de la pente augmente. Si l'on prend en considération qu'un large pourcentage des précipitations atmosphériques se dépense en évaporation, il en suit qu'au compte de l'écoulement souterrain revient, même dans les conditions de beaucoup de pays montagneux, seulement quelque pour cent (en moyenne près de 5). C'est seulement dans les régions de Karst où l'on observe une rapide absorption des eaux superficielles que cette quantité peut être beaucoup plus importante.

Les particularités de l'hydrogéologie des systèmes naturels d'eaux en charge complexes des pays montagneux et le degré d'intensité de lavage des roches dépendent de l'histoire géologique, de l'âge, aussi bien que du caractère des formations qui composent tel ou tel édifice et de l'intensité de son élèvement. En particulier, au Caucase où les grands soulèvements eurent lieu au Quaternaire et continuent jusqu'à nos jours, les dépôts marins sédimentaires du Jurasique, du Paléogène et du Néogène conservent jusqu'aux temps actuels encore le complexe ancien de sel de type marin, qui exerce une influence prononcée sur la composition des eaux coulantes. Mais les édifices anciens ont depuis longtemps subi des lavages et donnent des eaux de minéralisation extrêmement faible.

Les régions montagneuses par suite du soulèvement des couches et du démembrement profond par le réseau érosif (vallées, gorges, canyons) se distinguent par une fragmentation des conditions hydrogéologique. Elles représentent *des bassins d'eaux souterraines* comparativement petits et liés les uns aux autres, qui en maints cas portent le caractère de bassins artésiens ou de courants et de bassins d'eaux de sous-sol « superposés ». Parmi ceux-ci on rencontre de plus grands bassins artésiens qui se rapportent à des dépressions entre les montagnes généralement remplies par de puissantes accumulations poreuses.

Le bassin artésien à multiples étages le plus remarquaqle, situé sur le territoire de l'URSS, est celui de Fergana, à superficie de 40000 mètres carrés.

Des bassins artésiens asymétriques ou des pentes artésiennes appartenant aux couches incidentes en monoclinale s'observent le plus souvent dans les parties de bordure des édifices montagneux. Un des plus puissants bassins asymétriques du type de pente artésian est situé dans les limites du monoclinale Caucase septentrional. Avec un large développement de roches éruptives cristallines se créent des systèmes natureles d'eaux en charge, dans des fissures du type artésien, mais à conditions un peu plus complexes, car le mouvement des eaux se rapporte aux systèmes de fissures et de fractures ou à des contacts de roches éruptives et sédimentaires.*

Sur les cartes hydrogéologiques et sur les coupes des régions montagneuses on établit d'une manière aboslument précise les dimensions des bassins et tous leurs éléments. Tout d'abord se dessinent bien les régions *d'infiltration contemporaine* des eaux atmosphériques (« région d'alimentation ») et les terrains d'écoulement ou de *déchargement* des eaux souterraines, exprimés par des sources multiples. L'élaboration des cartes pour les sources qui peut être faite par méthode d'aérophotographie permet de bien évaluer combien les terres différentes sont aquifères et de calculer le *module d'écoulement* souterrain (en litres par secondes pour chaque mètre carré de l'horizon aquifère) pour les différents bassins des régions montagneuses. Généralement, le plus grand module d'écoulement souterrain ($1\text{-}2^1$/sec par 1 klm^2) s'observe dans les roches carbonatées fissurées. Le relèvement sur des cartes hydrogéologiques des sources et de toutes les autres manifestations des eaux, ainsi que le contournement des bassins et des versants artésiens permet de faire une évaluation quantitative des ressources en eaux souterraines.

Ayant connaissance du débit des sources et du module d'écoulement souterrain, on peut se faire une idée déterminée des dimensions du bassin d'alimentation. Durant les dernières années, à la suite des grandes quantités de tours de sondage se créent des foyers artificiels de déchargement d'eaux souterraines, qui influencent d'une manière très prononcée le débit des sources naturelles.

Les pays montagneux représentent soi-disant un gigantesque appareil naturel pour déterminer les propriétés de filtrage des roches et cet appareil fonctionne pendant un long laps de temps géologique. C'est pourquoi la systématisation du matériel concernant les sources des régions montagneuses, l'analyse de leur composition, l'inventaire du débit, de la température permettent d'établir d'une manière quasi précise le degré de l'abondance en eau de chaque complexe aquifère et même de toute une formation entière, d'évaluer le rôle hydrogéologique des différents accidents et, par conséquent, de marquer correctement les terrains les plus favorables pour l'exploitation et les perspectives d'utilisation ultérieure des eaux souterraines. Dans maintes régions montagneuses on remarque l'importance hydrogéologique prononcée des *zones d'extension* des roches et la création de terrains les plus aquifères dans les points de fractures transverales et en diagonale (le Caucase, le Kopet-dag).

Les cartes hydrogéologiques des régions montagneuses doivent désigner clairement tous les principaux complexes aquifères perméables et impérmeables et avoir des isolignes montrant le recouvrement de ces complexes (stratoisogypses). Ces lignes, ainsi que les lignes de partage superficiel et souterrain des eaux, soulignent bien le caractère des bassins et le rapport des foyers de déchargement des eaux à telles ou telles structures géologiques et aux éléments du pays montagneux. On montre aussi sur les cartes le dynamisme des eaux souterraines, exprimé par les *hydroisogypses* et les *isopiezes* pour le complexe aquifère principal. De telles cartes permettent de se

(*) Ota Hynic. Vodarensky vyuzitelné vydatné vàdzre podzemnich vod v cechach. « *Geotechnica* ». S. 8. Praha. 1949.

représenter clairement la direction du mouvement des eaux souterraines, la modification du degré de l'abondance en eau des complexes et la forme des dépressions qui se créent dans les foyers de déchargement naturel ou artificiel des eaux souterraines.

L'analyse des cartes hydrogéologiques des régions montagneuses a amené l'auteur de cet exposé à la conclusion suivante : les parties des terrains ressortants des massifs de roches perméables ne représentent pas simplement une région d'infiltration actuelle des eaux atmosphériques, mais aussi *une région oû se crée la pression hydrostatique*, qui se transmet sur tout le bassin des eaux souterrraines et attire vers la surface non seulement les eaux jeunes, mais aussi les eaux anciennes des parties fermées des structures. La loi établie a une grande importance pour la caractéristique du dynamisme des eaux souterraines, car dans les zones des foyers de déchargement d'eau sous pression qui prennent naissance dans les vallées et les gorges particulièrement dans les parties de bordure des bassins, on peut observer le mouvement des eaux souterraines, dirigé vers les massifs ressortants sur une distance de dizaines de km.

La zonalité hydrogéologique et hydrogéochimique des régions montagneuses est exprimée d'une manière plus complexe en comparaison à celle qui s'observe dans les limites des régions en plate-forme. Cela s'explique par les conditions paléohydrogéologiques et par le régime des mouvements oscillatoires qui créent des conditions variées pour le lavage des différents complexes selon le degré de leur perméabilité. Dans les limites des bassins des pays montagneux il est très difficile d'établir la borne entre la zone de l'échangement intensif d'eau et la zone de l'échangement ralenti; mais la zone d'échangement d'eau très ralenti, avec laquelle sont ordinairement liées les saumures fortement minéralisées, est presque toujours absente dans les limites des régions montagneuses; une exception a peut-être lieu dans les grandes dépressions entre les montagnes. Par place on observe. par contre, une situation inverse; c'est-à-dire « une inversion des zones » exprimée par ce que les complexes supérieurs se trouvent moins lavés que les inférieurs, dans lesquels peuvent être comprises des eaux faiblement minéralisées et même, par place, des eaux douces.

Les conditions hydrogéologiques les plus complexes se créent dans les édifices montagneux à plissements d'âge alpin compliqués par des néointrusions, par des volcans et des épanchements de laves. Souvent les intrusions représentent des foyers complexes originaux de déchargement des eaux artésiennes profondes en manière de grands « bouchons » de pas très forte densité; l'eau traverse ces « bouchons » sur la surface le long du contact des roches effusives et sédimentaires, ou bien le long des fissures tectoniques. On peut observer le plus clairement la manifestation des néointrusions et leurs influences sur les conditions hydrogéologiques du versant artésien à l'exemple du disctrict admirable — les Eaux Minérales Caucasiennes (Caucase Septentrional). En cas de développement d'épanchements de laves, de couvertures de laves et d'amoncellement de brèches de tufs et de laves, on peut observer la formation de bassins puissants d'eaux souterraines; leurs réserves peuvent être utilisées pour alimenter les grands centres de population. Un tel tableau s'observe dans les limites des champs de laves en Arménie et sur les îles Hawai *). Encore plus compliquées sont les conditions hydrogéologiques en présence de glaçage, avec lequel est lié un complétement systématique des ressources en eaux souterraines durant la fonte d'été des glaciers. L'entraînement de matériel friable dans les contreforts et dans les dépressions entre les montagnes créent des conditions favorables pour former des lots de terres très aquifères dans telles places, où les eaux souterraines sont utilisées en large mesure pour l'alimentation en eau des centres habités et pour

(*) Cox Doan C. Research in ground water hydrology in Hawaii. *Pacif. Sci.* 1954. N. 2.

irrigation (les versants du Caucase Sud-Est, les contreforts du Thian-Chan, les montagnes Atlas au Maroc*, etc.).

La congélation « merzlota » de plusieurs années, développée en certaines régions montagneuses jusqu'à une profondeur de plusieurs centaines de mètres, crée des conditions hydrogéologiques particulières, qui ne peuvent être examinées en détail dans l'exposé donné. En même temps il est nécessaire de noter qu'en présence d'une tectonique compliquée dans de telles régions se créent des foyers localisés de déchargement, exprimés par des grandes « naledj » (sorte de langues des glaciers). La fonte de ces dernières en été laisse son empreinte sur le régime des eaux dans ces régions (P. F. Schvetsov). En élaborant des cartes hydrogéologiques des régions montagneuses à congélation de plusieurs années, tous les phénomènes, liés aux particularités du développement des eaux souterraines, doivent être montrés sur la carte (sources d'eaux au-dessus des congélations, entre les congélations, au-dessous des congélations; monticules de gonflement, hydrolacollites, etc.).

Dans les limites des régions montagneuses sont compris les *gisements* les plus importants *d'eaux minérales*, souvent tièdes ou chaudes (et par place même surchauffées, à température de plus de 100° C) ayant une grande portée dans l'économie nationale. Beaucoup d'entre eux ont servi de base pour le développement des stations thermales balnéaires. La présence de foyers magmatiques situés à courte distance et encore point refroidis fait que les eaux souterraines prennent près de la surface terrestre une haute température et se manifestent dans les foyers de déchargement comme *hydrothermes* modernes comprenant beaucoup de composants en minérais de valeur. Les contours des gisements d'eaux minérales se montrent sur les cartes hydrogéologiques par les isolignes générales de minéralisation ou par les contenus de différents éléments (d'arsenic, de bore, de chlore, de brome et de iode, etc.); cela permet de connaître le volume de ces gisements et de faire une évaluation plus correcte des ressources en eaux minérales. Les gisements d'eaux minérales situées dans les limites des bassins de régions montagneuses entrent dans les provinces hydrochimiques plus grandes, leurs limites se tracent sur des cartes hydrogéochimiques spéciales. Il faut aussi montrer sur ces cartes les enrichissements des eaux minérales par des composants spécifiques (tels qu'hydrogène sulfuré, fluor, etc.). Les régions des eaux *carboniquées* saturées d'acide carbonique d'origine métamorphique peuvent être contournées le plus distinctement dans les limites des régions montagneuses et à leurs bordures dans la sphère des foyers des néointrusions (Le Grand Caucase, les Sayannes Orientales, le Sihkoté-Aline, les Pyrénées Sud-Est, etc.). Des régions d'eaux *azotiques*, le plus souvent thermales, se rapportent aux massifs fissurés de roches éruptives volcanogènes ou métamorphiques; elles sont liées à une pénétration profonde de l'air atmosphérique dans les eaux souterraines (Thian-Shan, Altai et autres). Elle sont souvent enclavées dans les régions d'eaux carboniquées ou bien elles entourent ces dernières. Les régions des eaux à méthane se disposent sur les terres abaissées et dans les contreforts, où elles sont insérées par places dans les roches sédimentaires des dépôts de pétrole et de gaz. On observe le plus distinctement dans le Grand Caucase une répartition zonale concentrique des régions d'eaux minérales à compositions gazeuses différentes. Au centre du Caucase se trouve une région d'eaux carboniquées, entourée par des régions d'eaux azotiques; sur la périphérie se dispose une ceinture d'eaux de méthane. Un tableau analogue, mais moins distinct de zonalité des eaux minérales, s'observe dans la chaîne de montagnes Elbourse (Iran), où les eaux carboniquées créent une région comparativement petite auprès d'un énorme volcan éteint du Demavende.

(*) Hydrogéologie du Maroc. XIX° Congrès Géologiques International. (R. Ambroggi, Ed. Bolelli, R. R. Bourgin etc...) Rabat. 1952.
La géologie et les problèmes de l'Eau en Algérie. Données sur l'Hydrogéologie Algérienne (M. Gautier, A. Cornet, N. Gouskovucts). Alger 1952.

Les eaux souterraines à contenu élevé en éléments radioactifs se rapportent en telle ou telle mesure aux intrusifs acides ou aux produits de leur destruction. Parmi les eaux radioactives, on peut rencontrer des eaux froides de sous-sol, ainsi que des eaux de fissures à pression thermales. Une grande importance a l'établissement du caractère de la présence dans les roches d'éléments radioactifs — en état dispersé ou bien sous forme d'accumulations secondaires. Dans ce dernier cas, les eaux possèdent souvent une radioactivité plus élevée. La tâche des hydrogéologues au cours des investigations *radio-hydrogéologiques* consiste en un tracé correct des *aires de dispersion* des éléments radioactifs dans les eaux souterraines (du radonium, du radium, de l'uranium, etc.). Ces aires sont presque toujours allongés dans la direction du mouvement des eaux souterraines et forment des contours en ovales irréguliers, en formes de secteurs, d'éventails ou des traînes. Les foyers d'enrichissements maximum des eaux par le radonium se rapportent souvent aux places où se sont déposés les collecteurs d'émanation en combinaison aux secteurs de roches à très faibles propriétés de filtration.

L'élaboration des cartes hydrogéologiques des régions montagneuses demande une utilisation des plus parfaites de méthodes de la cartographie contemporaine. Une carte hydrogéologique se distingue, comme on le sait, d'une carte géologique en ce qu'elle reflète la combinaison de trois éléments : de la structure géologique, du relief et de l'eau. Par conséquent, l'élément principal sur les cartes hydrogéologiques — l'eau souterraine — est un élément mobile qui se trouve en état dynamique et qui se modifie dans le temps.

La cartographie des pays montagneux au cours des années à différents degrés de sécheresse et même en diverses saisons d'une même année (printemps, été, automne) montre comment la notion de l'abondance en eau du district ou le contenu « de fonds » d'un tel ou tel élément peut se modifier et comment cela peut se faire sentir dans la direction des travaux de recherches si on y applique des méthodes hydrogéochimiques.

Les cartes hydrogéologiques doivent se complémenter de coupes et de diagrammes en block refletant les particularités de la déposition et du dynamisme des eaux souterraines pour une période de temps définie (isogypses, isopiezes, isotermes, isochlorides, isorades, etc.). Pour dresser des cartes hydrogéologiques, on utilise tous les genres de cartes — géologiques, tectoniques, climatiques, gypsométriques, géomorphologiques, hydrologiques, géobotaniques, des cartes de roches utiles, etc. Néanmains il faut prendre en considération que les conditions hydrogéologiques des bassins d'eaux souterraines sont soumises à leurs propres lois, liées aux processus de l'alimentation et de la formation des eaux souterraines, à leur dynamisme et à leur régime.

Il n'est aucunement obligatoire que les bordures des bassins d'eaux souterraines coïncident toujours avec les lignes de partages superficielles ou bien avec des contacts des différentes séries. A certaines places, on peut remarquer une relation intérieure, plus profonde entre les différents bassins. Rien qu'une mise en valeur créatrice de tout le matériel qui caractérise les lois de répartion des eaux souterraines de types variés peut permettre d'elaborer de bonnes cartes hydrogéologiques pour les régions montagneuses, pouvant servir de base à une évaluation quantitative des ressources en eaux souterraines.

Dans la pratique des investigations hydrogéologiques, la méthode d'elaborer des cartes *parallèles* qui permettent *d'analyser* les différents éléments de la vie des eaux souterraines (variations des niveaux, minéralisation, etc.) a trouvé une large application. Les généralisations ultérieures se font sur des cartes *synthétiques* où l'on montre des combinaisons de plusieurs éléments. Pour illustrer la composition chimique des eaux souterraines (en y marquant les composants principaux, certains microcomposants, la température, le contenu en gaz, le débit) on trace sur les cartes

des diagrammes circulaires ou rectangulaires à échelles définies, en raison de quoi se crée un cartodiagramme hydrogéologique.

Le degré de précision des cartes hydrogéologiques dressées et la charge des cartes de régions montagneuses dépendent de l'état de connaissance et de prospection et aussi des échelles adoptées pour les cartes. L'expérience a démontré que les échelles des cartes et leur but principal doivent être réglementés avec précision.

On distingue trois catégories de cartes hydrogéologiques : 1) à grandes échelles, 2) à échelles moyennes et 3) à petites échelles.

1. Les cartes hydrogéologiques à grandes échelles se dressent à 1:200000. Elles se divisent en a) cartes *détaillées* à échelles jusqu'à 1:25000, sur lesquelles on montre les parties des bassins et les différents foyers de déchargement, et b) en cartes de *superficies* à échelle 1:200000 et plus, sur lesquelles on peut montrer les superficies des différents bassins, les issues naturelles ou artificielles des eaux et les isolignes de recouvrement des principaux horizons aquifères. Pour le calcul des ressources en eaux souterraines il est tout-à-fait nécessaire d'élaborer des cartes hydrogéologiques à grandes échelles.

2. Les cartes à échelles moyennes (à partir de 1:200000 jusqu'à 1:1000000) permettent de montrer les différents districts hydrogéologiques des pays montagneux, leurs particularités, de distinguer les districts ayant le plus de perspectives pour faire des travaux détaillés.

3. Les cartes à petites échelles, de revue (moins de 1:1000000) illustrant les lois générales de repartitions des eaux souterraines, sur lesquelles on peut montrer les grandes provinces ou les régions à eaux souterraines.

Il est nécessaire pour élaborer les cartes hydrogéologiques que a) les signes conventionnels de la légende et de la carte soient simples et distincts, b) que la couleur des désignations corresponde aux coloriages généralement adoptés pour l'échelle stratigraphique et c) que les signes montrent le degré variable de l'abondance en eau et qu'ils permettent de superposer les désignations. Par ailleurs les cartes hydrogéologiques ne doivent point être surchargées. La mesure de la charge portée par les cartes doit correspondre strictement à l'échelle et au type de la carte.

Les cartes hydrogéologiques des régions montagneuses peuvent être bien elaborées si l'on accepte une standardisation des signes conventionnels, comme cela est adopté depuis longtemps pour les cartes géologiques. Les désignations conventionnelles doivent être préparées préalablement, soumises à une discussion profonde et confirmées à la prochaine session du Congrès Géologique International en 1960. Ces désignations doivent refléter les succès atteints par le développement de l'hydrogéologie et les exigences les plus hautes en sens graphique.

A HORIZONTAL SCALE MODEL BASED ON THE VISCOUS FLOW ANALOGY FOR STUDYING GROUNDWATER FLOW IN AN AQUIFER HAVING STORAGE

G. SANTING
Chief-Engineer,
Netherlands Government Institute for Water Supply.

Abstract

A scale model is described which was developed with the aim to solve problems connected with groundwater flow in aquifers with storage.

The model is based on the Hele-Shaw analogy, where groundwater flow is imitated by a laminar flow of a viscous liquid through a narrow interspace between two plates. Storage is introduced by means of storage vessels connected to the interspace.

This type of model can be used for studying both steady and non-steady groundwater flows under the effects of rainfall, evaporation, pumping, artificial recharge, tidal fluctuations, etc. The aquifers simulated by the model may be confined or phreatic and homogeneous or non-homogeneous with respect to transmissivity and storage capacity. Limitations to the applicability of the model are few and result mainly from the fact that the flow through the interspace is two-dimensional only and that the transmissivity of the interspace is constant in time.

Introduction

The viscous flow analogy as a means for investigating groundwater flow problems is known already for a long time (Hele-Shaw, 1897). Its use is based on the fact that a two-dimensional laminar flow of groundwater through a porous soil can be expressed by the same differential equation as the laminar flow of a viscous fluid through a narrow interspace between two parallel plates. Since this principle was explained already a great many times (Dachler 1936, Günther 1940, Dietz 1941, Santing 1951 and others), it will not be discussed again in the present paper.

Scale models, based on this principle, consist in their simplest form of two closely spaced parallel transparent plates, which thus form a narrow channel through which a viscous liquid is flowing.

When put in a vertical position and closed at the bottom (fig. 1), this model may represent a cross section through a phreatic aquifer where a two-dimensional groundwater flow is present; the interspace between the two model plates simulates the porous soil and the liquid in the interspace represents the groundwater. The two-dimensional potential flow field of the liquid in the interspace is a picture of the potential flow field of the two-dimensional groundwater flow in the cross section represented by the channel.

This type of model was developed further in recent years to study a great many steady and non-steady flow problems in two-dimensional cross-sections (Dietz 1941, Santing 1951). Rainfall can be imitated by sprinkling over the length of the channel (see *c* in fig. 1); groundwater withdrawal or artificial replenishment may be imitated by withdrawing or adding liquid at the respective places in the channel (*d* in fig. 1); variations in fluid levels can be realized by means of reservoirs which are vertically adjustable and connected to the interspace (*g*); variations in the hydraulic conductivity of the soil can be imitated by variations of the width of the interspace; the

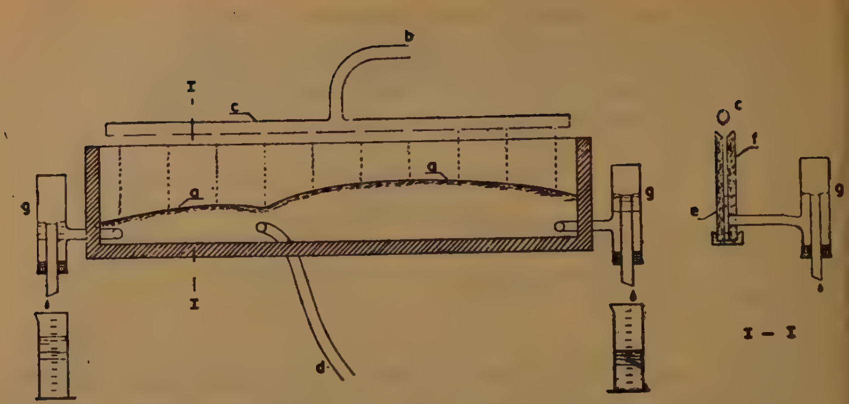


Fig. 1 — *Vertical viscous flow analogy.*
a = groundwater table.
b = supply of rain.
c = sprinkler.
d = discharge tube.
e = viscous liquid.
f = transparent plates.
g = vertically adjustable overflow.
I — I = cross section I — I.

storage capacity of the soil above the phreatic surface is represented by the storage capacity of the interspace above the fluid level; two fluids of slightly different density can be used for imitating fresh and salt groundwater; etc.

When the model is put in a horizontal position, it may represent a certain areal extent of an aquifer which may be either phreatic or confined. The interspace imitates the aquifer; the plate spacing is related to the value of the transmissivity of the aquifer. Local variations of the transmissivity can be introduced by variations in the width of the interspace. Models if this type have been used little, since mainly steady-state problems can be studied by means of them, due to the absence of storage capacity in the horizontal channel between the two plates. In the Hydrological Laboratory of the Netherlands Government Institute for Water Supply this model, therefore, was improved and provided with a means for imitating storage, with a view to using this model for studying the effects of artificial recharge of the groundwater in a well field in the province of Zealand.

Description of the model

The basic parts of the model (fig. 2 *a*) are the two horizontal plates, which enclose the interspace, and a great number of small vessels on top of the upper plate and connected to the interspace.

The interspace is representative of the transmissivity of the aquifer. The vessels on top of the model introduce storage capacity; a rise of the level of the liquid in the vessels means that liquid is stored, a drop means a release from storage. So the two main hydraulic properties of an aquifer, viz. its transmissivity and its storage capacity, are present in the model, although realized by separate means.

In most cases the storage vessels will be all of the same size and equally spaced on the upper plate of the model, thus representing an area with uniform storage

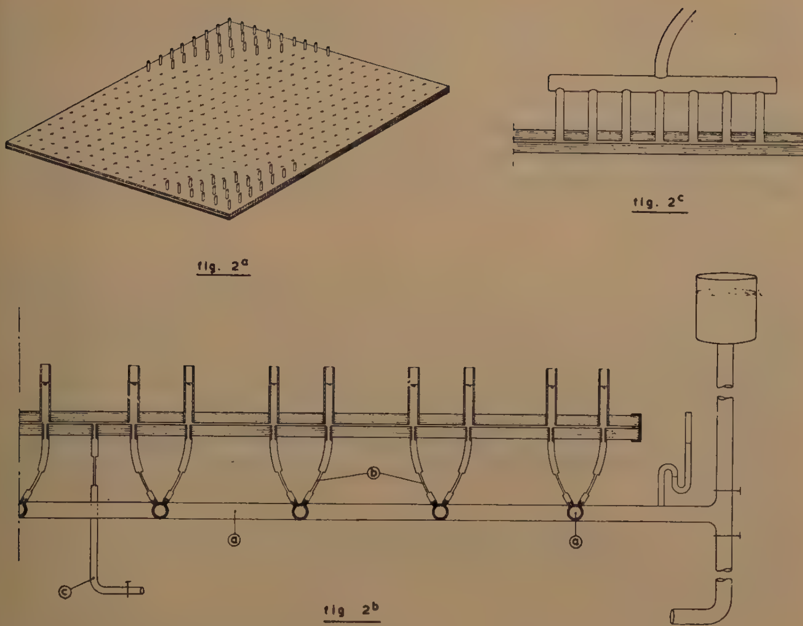


Fig. 2 — *Horizontal viscous flow analogy.*
Fig. 2*a*. View from above on the plates with the storage vessels.
Fig. 2*b*. Cross section through plates.
a = distribution system for rainfall and evaporation.
b = capillary tubes.
c = discharge or supply tube.
Fig. 2*c*. Connections, imitating drainage or infiltration canal.

capacity. Variations in storage capacity may however be realized by variations either in spacing or in the diameters of the vessels.

As has already been said, a model of this type may represent either a phreatic or a confined aquifer. In the first mentioned case the storage capacity of the storage vessels has to correspond (on a certain scale) with the storage capacity of the soil above the groundwater table; in the second case it corresponds with the elastic storage capacity of the confined aquifer. In both cases the level of the liquid in the vessels represents the groundwater potential. The vessels can therefore be used as observation wells for level readings.

Further parts of the model are the means for imitating the replenishment of the groundwater by rainfall and the loss by evapotranspiration — the two only in the case of phreatic groundwater—, the withdrawal through wells, artificial recharge, the natural fluctuations of the groundwater level at the boundaries of the area, etc.

The effects of rainfall and evapotranspiration can be realized in the model by supplying or withdrawing certain quantities of liquid by means of a system of distribution tubes placed under the model and connected to the interspace at a great many places (see *a* in fig. 2*b*). This distribution system is placed under the model plates in order to keep the area above the plates free from tubes which might hinder the level readings. The introduction of rainfall and evaporation from below instead of from above does not affect the two-dimensional flow pattern in the interspace. The

connections of the distribution system to the interspace were made just below the storage vessels. That way the liquid supplied or withdrawn through the distribution system can immediately be stored or released from storage in the storage vessels without having to pass horizontally through the interspace first and by that causing an undesirable deviation of the potentials.

The amounts of liquid supplied or withdrawn through the distribution system may be regulated by means of a pressure regulator or, as is shown in fig. 2*b*, by valves in connection with a manometer. Thus seasonal or other variations in rainfall and evaporation can easily be simulated. The computation of the quantities of liquid will be dealt with later.

The quantities supplied or withdrawn should be independent of the accidental pressure of the liquid in the interspace, i.e. the level of the liquid in the storage vessels. This means that the variations in the pressure of the liquid in the interspace during the experiment should be negligibly small as compared with the pressured head needed for the flow through the distribution system. To that end this potential head was increased greatly by inserting in the distribution system capillary tubes which offer a large resistance to flow (*b* in fig. 2*b*).

Withdrawal of groundwater through wells or artificial replenishment by means of recharge wells can be imitated in the model by withdrawing or supplying certain amounts of liquid through tubes connected to the interspace at the corresponding locations (*c* in fig. 2*b*). Also these tubes are provided with capillary tubes in order to increase the pressure head required for the flow through them to such an extent that the accidental variations in the pressure of the liquid in the interspace may be regarded as negligible.

In case drainage or infiltration canals have to be imitated, a series of connections to the interspace following the course of the canal are made, as shown in fig. 2*c*. These connections can be made either through the upper or through the lower model plate.

The imitation of the natural fluctuations of the groundwater at the boundaries of the area is realized by connecting the storage vessels at these boundaries to level regulators, i.e. vertically adjustable vessels with a fixed level as shown in fig. 1 (*g*). The tubes connecting these regulators to the storage vessels should have a negligible resistance to flow, so that the level in the regulator corresponds exactly with the required level in the storage vessels.

Limitations to the applicability and accuracy of the model

There are several important limitations to the applicability and the accuracy of the model.

In the first place, after the model has been assembled, the width of the interspace is fixed. This means, that the value of the transmissivity, although it may vary from place to place, is fixed as well. The model therefore requires the condition that in case of phreatic groundwater the variations in the groundwater table are negligibly small as compared to the thickness of the aquifer and do not effect the value of its transmissivity.

A second restriction to the applicability and accuray of the model is caused by the fact that its storage capacity is not distributed uniformly over its area but is concentrated in a number of storage vessels. Non-steady flow through the aquifer, if imitated in the model, will therefore produce additional flows through the interspace from or towards the storage vessels, which are superimposed on the imitated flow field. These superimposed additional flow fields cause deviations from the

correct potentials. The closer the storage vessels are spaced, the smaller these deviations will be. For this reason the spacing should be chosen as such that the deviations generally are negligible.

It is obvious that the deviations from the correct potentials are largest in the immediate vicinity of wells, canals, rivers, etc. Here they generally may not be neglected. The potential flow fields in those places therefore cannot be reproduced correctly in the model. For this reason boundary conditions connected to wells, rivers and canals should as a rule not be expressed in potentials of the groundwater but in quantities.

Calculation of model scales

The relations for the model scales follow from the condition, that the ratio between any term in the general differential equation for groundwater flow and its corresponding term in the equation for the flow in the model should be the same.

The general differential equation for two-dimensional non-steady flow in a phreatic aquifer replenished by rainfall, reads as follows (under the condition that the variations in the groundwater level are negligibly small as compared with the thickness of the aquifer):

$$T\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}\right)+R=S\,\frac{\partial\psi}{\partial t}, \tag{1}$$

where

T = transmissivity of the aquifer;
ψ = potential of the groundwater;
x,y = horizontal co-ordinates;
R = replenishment by rainfall;
S = storage capacity of the aquifer;
t = time.

For the two-dimensional non-steady flow in a confined aquifer the same relation may be used, if R is put zero.

The corresponding equation for the flow in the model reads:

$$T_m\left(\frac{\partial^2\psi_m}{\partial x^2_m}+\frac{\partial^2\psi_m}{\partial y^2_m}\right)+R_m=S_m\,\frac{\partial\psi_m}{\partial t_m}, \tag{2}$$

where the index m refers to the model.

The «transmissivity» of the interspace between the model plates, T_m, may be written as follows, according to the law of Poiseuille;

$$T_m=\frac{\rho g b^3}{12\eta}, \tag{3}$$

where

ρ = density of the liquid used;
η = its dynamic viscosity;
g = gravity;
b = width of the interspace.

The storage capacity of the model, S_m, may be defined as the amount of liquid released from storage by a unit decline of potential head. From this it follows that S_m is the ratio between the area of the storage vessels and the area of the model plates. If r is the inner diameter of a storage vessel and the vessels are spaced in such

a way that each of them holds the storage of an area A, the storage capacity of the model is

$$S_m = \frac{\pi r^2}{A} \tag{4}$$

The relations for the model scales following from the equations (1) and (2), are

$$N_T \frac{N_\varphi}{N^2} = N_T \frac{N_\varphi}{N_y^2} = N_R = N_S \frac{N_\varphi}{N_t}, \tag{5}$$

where

N = scale, or model-prototype ratio (N_T for transmissivity, N_φ for potential, etc.)

Since this are three relations between seven scales, four of the latter may be chosen freely. Those four will generally be N_t, N_φ, N_x (or N_y) and N_S. The time scale N_t will be chosen such that during the model experiment sufficient time is available for the readings and the other operations. The scale for the potential N_φ has to be selected such that the level readings can be sufficiently accurate. The condition that the model should have manageable dimensions determines the horizontal scale N_x (or N_y). The storage scale chosen, N_S, should permit a spacing and diameter of the storage vessels which are justified both from a hydraulic and from a technical point of view; e.g. a too small number of vessels would result in too large deviations from the correct potentials of the flow field; storage vessels of too large diameter would hamper the readings during the experiments.

After these four scales have been chosen, the other three can be computed from (5). In addition to the scales mentioned in (5), also the discharge scale N_Q and the volume scale N_v are needed. The former can easily be derived from any discharge formula, as e.g. the equation for two-dimensional groundwater flow

$$Q = B\,T \frac{d\varphi}{dx},$$

where Q denotes the discharge across a section of the aquifer of a length B. From this equation the following relation for the scale results

$$N_Q = N_y N_T \frac{N_\varphi}{N_x} = N_T\, N_\varphi \tag{6}$$

The volume scale follows of course from

$$N_V = N_Q\, N_t\,. \tag{7}$$

It is evident that, for phreatic conditions,

$$N_R = \frac{N_Q}{N_x N_y} \tag{8}$$

The final stage in designing the model is the determination of the width of the interspace, the kind of liquid to be used and the diameter and spacing of the storage vessels.

The width of the interspace and the model liquid have to fulfil the following conditions:

a. the values of b, η (at the average temperature during the model experiments) and ρ should satisfy equation (3);

b. the flow through the interspace should be laminar, which implies that the Reynolds number has to be smaller than about 1.000.

Several liquids and a range of values for the width of the interspace will comply with these conditions. The most appropriate liquid and width of interspace can however easily be determined if also a number of additional practical requirements are taken into account. Such additional conditions demand e.g. that the interspace should not be too narrow in order to avoid constructional difficulties, and that the viscosity of the liquid is effected as little as possible by changes in temperature or other influences (humidity, light, dying etc.).

It should be remarked that a change in temperature changes the viscosity of the model liquid and consequently changes the time scale too. The temperature therefore is observed very carefully during the experiments and is kept as constant as possible.

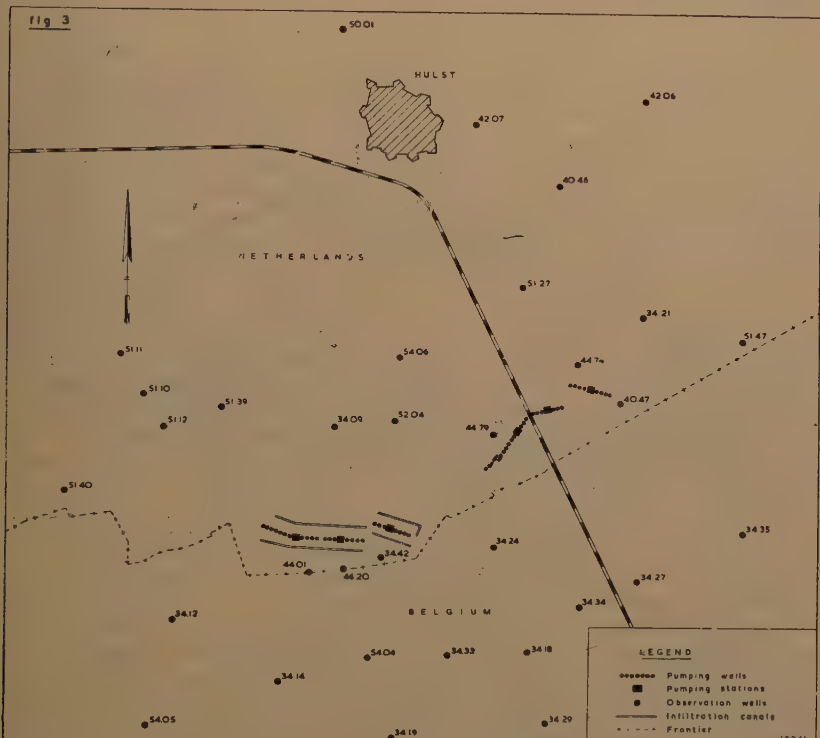


Fig. 3 — *Map showing location of well fields and infiltration canals of Zealand Flanders Waterworks Company.*

Examples

The first time this type of model was used, was for the purpose of investigating the effects of artificial replenishment of the phreatic groundwater in the well fields of the Waterworks Company of Zealand Flanders. (fig. 3).

The groundwater in the area considered occurs in a shallow sandy aquifer, underlain by impervious clay beds. The thickness of the aquifer amounts to only 7 to 25 m; the permeability of the sand, as determined from the results of pumping tests and water balance computations, is about 8,5 m/day. The value of the storage

capacity of the phreatic aquifer was not quite certain, but was supposed to be between 0,2 and 0,3.

The groundwater is tapped by means of several series of small wells, as indicated on the map (fig. 3). Infiltration canals for the artificial replenishment of the aquifer are present along either side of three of these series of wells at a distance of 100 m from them.

In winter some 0,8 million m³ of surface water are infiltrated in these canals. In summer infiltration is stopped because of lack of surface water of good quality. The total quantity of groundwater withdrawn from the aquifer averages about 2,5 million m³/year.

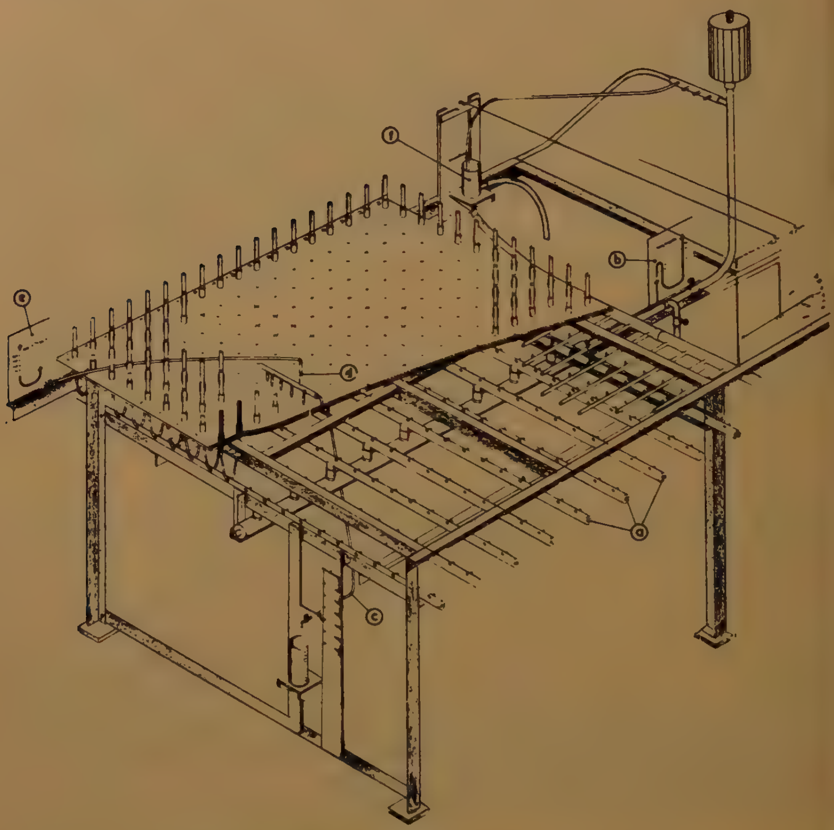


Fig. 4 — *Horizontal scale model used for the investigations for the Zealand Flanders Waterworks.*

a = distribution system for rainfall and evaporation.
b = mercury manometer for regulating supply of rain or withdrawal of evaporation.
c = discharge tube with tap on vertically adjustable slide, for imitating groundwater pumping station.
d = supply system for imitating infiltration canal.
e = manometer for regulating the supply to infiltration canal.
f = vertically adjustable overflow vessel connected to boundary of model, for regulating fluctuating levels.

The aim of the model experiments was to determine the yield of the aquifer under various conditions of rainfall, if the artificial replenishment of the groundwater in winter was increased from the present 0,8 million m^3 per year to 1,5 million m^3 per year.

The model constructed for this purpose (fig. 4) had to represent an area of 55 km^2 (7,5 km $\times$ 7,5 km), in the centre of which the series of wells and the infiltration canals are situated. For practical reasons the dimensions of the horizontal model plates were chosen 2 m $\times$ 2 m. This resulted in a horizontal scale $N_x = N_y = \frac{1}{3750}$.

The potential scale was fixed at 1/100; thus 1 mm in the model represented 0,1 m in the field. This was considered sufficiently accurate for the imitation of the groundwater fluctuations.

The time scale was chosen as such that a month would be represented in the model by about 20 seconds. This would allow to carry out all necessary operations and readings during the experiment.

The other scales could be computed from the scale relations (5). After that the technical details of the model could be determined. The plates were made of transparent plastic, 8 mm thick. The interspace between the plates had to represent the aquifer with its depth varying between 7 and 25 m. Therefore the width of the interspace could not have the same value all over the area of the model, but was chosen varying from 0,8 mm to 1,25 mm. (The variations in width can be determined from (3)).

As model liquid Shell Vitrea oil 72 was taken. This liquid has a kinematic viscosity (η/ρ) of 10,8 stokes at a temperature of 15° C, 6,95 stokes at 20° C and 4,7 stokes at 25° C.

The storage capacity of the model was obtained by means of plastic storage vessels with an inner diameter of 16 mm, at a spacing of 0,1 m. In a small area of the model, representing an area where the aquifer is covered by a clay layer and no rain can percolate into it, the rain and evaporation system was not connected to the interspace.

Other details of the model are shown in fig. 4.

The first series of experiments carried out on this model aimed at testing the model and verifying the hydrologic constants. In the first place the average flow conditions were imitated, i.e. steady state flow with average rainfall, average evaporation, average pumpage, average artificial replenishment and average groundwater levels at the boundaries of the area. From these experiments it was found that the effective precipitation (i.e. rainfall minus evaporation) is much smaller than it was supposed to be before. This conclusion was supported by the results of recent meteorological and drainage basin studies.

After that the actual conditions in a number of recent years were imitated and the results compared with the data obtained in the field. As could be expected because of the uncertainty regarding the value of the storage capacity of the area, the first experiment did not yet give satisfactory results. A good agrreement with the data obtained in the field was arrived at only by trial and error.viz. by varying the time scale until the results of the experiment were in accordance with the field date.

Since the time scale varies with the storage scale—as is apparent from (5)—the value of the storage capacity of the area could be determined from the correct time scale. A value of 0,22 was obtained that way.

After these preliminary experiments the effect of increased artificial replenishment on the yield of the aquifer could be investigated. The results of these experiments

gave valuable information on which the future exploitation scheme of the Waterworks Company could be based.

A second subject now being investigated with the aid of the horizontal scale model, is the effect of irrigation on the groundwater level and the losses of irrigation water by underground flow in an agricultural area in the province of Limburg.

ACKNOWLEDGMENT

The author wishes to thank Mr. J. Bear, Haifa, and Mr. M.P.C. van Overstraten Kruysse, The Hague, for their co-operation in developing and building the first model and carrying out the experiments.

LITERATURE REFERENCES

HELE-SHAW, H. S., 1897, Experiments on the nature of the surface resistance in pipes and on ships, *Trans. Inst. Naval Architects*, vol. 39, pp. 145-156.

DACHLER, R., 1936, Grundwasserströmung, J. Springer Verlag, Vienna.

DIETZ, D. N., 1941, Een modelproef ter bestudering van niet-stationnaire bewegingen van het grondwater (A model experiment for studying non-steady movements of groundwater), *Water* (Netherlands), vol. 25, No. 23.

SANTING, G., 1951, Modèle pour l'étude des problèmes de l'écoulement simultané des eaux souterraines douces et salées, Proceedings General Assembly Brussels of the International Assoc. of Hydrology, Internl. Union of Geodesy and Geophysics, vol. II, pp. 184-193.

ELEMENTS POUR L'ETABLISSEMENT DU BILAN DE LA NAPPE PHREATIQUE DE LA PLAINE DES TRIFFA
(Maroc Oriental)

F. MORTIER
Ingénieur Géologue au Centre des Etudes Hydrogéologiques du Maroc

SOMMAIRE

L'essai d'établissement d'un bilan de la nappe phréatique des Triffa (alimentation d'une part, prélèvements et exutoires d'autre part), est proposé comme méthode de première approximation, permettant d'évaluer par une étude critique de mesures diverses (pluviométrie, statistiques de pompage, jaugeages) l'ordre de grandeur des ressources en eau souterraine de la plaine. Les moyens de réduire les incertitudes de chacun des éléments du bilan (en particulier pour le coefficient d'infiltration qui intervient dans l'évaluation de l'alimentation) sont passés en revue : l'interprétation des variations du niveau de la nappe en fonction de la pluviométrie et l'étude mathématique d'essais de pompage dans diverses zones permettront de préciser ce bilan provisoire.

INTRODUCTION

Pour la mise en valeur d'un pays semi-aride comme le Maroc où les ressources en eaux souterraines représentent une proportion importante des eaux d'irrigation (d'après Ambroggi [1] le 1/3 environ des eaux de surface régularisables), il est d'une extrême importance de définir pour chaque unité hydrogéologique les quantités d'eaux souterraines économiquement utilisables — ceci, afin de ne pas permettre une surexploitation qui, parfois admissible en période humide, serait finalement nuisible à l'ensemble des utilisateurs.

C'est dans cet esprit que les pompages supérieurs à 200 m³/jour sont réglementés au Maroc.

L'essai d'établissement du bilan hydrologique d'une nappe est présenté ici comme une méthode peu onéreuse pour estimer avec une assez bonne approximation la quantité d'eau souterraine disponible dans une région donnée : c'est une méthode peu onéreuse car elle n'exige pas de travaux importants (géophysique, sondages) ni d'essais coûteux, et peut être mise en action par quelques agents rassemblant des renseignements climatologiques (température et précipitations), hydrologiques (jaugeages de sources et de rivières, surveillance de piézomètres) et économiques (sur l'utilisation de l'eau); ces mesures et ces statistiques sont ensuite transformées en éléments d'un bilan, celui des modalités de l'équilibre dynamique entre le débit d'alimentation et le débit des pertes artificielles et naturelles. Mais pour établir un bilan un tant soit peu précis, on doit d'une part avoir mené à bien une étude hydrogéologique mettant en évidence l'importance relative des différents éléments de l'actif et du passif du bilan, et d'autre part disposer de « moyennes » climatologiques et hydrologiques établies sur des mesures de plusieurs années.

L'essai d'établissement du bilan de la nappe phréatique des Triffa est ici présenté à titre d'exemple.

* * *

a) *Historique*

La plaine des Triffa, située à l'extrémité Nord-Est du Maroc dans la zone semi-aride (indice d'aridité De Martonne (1935) — 6,2) était couverte en 1908 d'une steppe de lentisque et de jujubier et son centre était marécageux (2).

La mise en valeur de cette plaine, d'une superficie de 750 Km² dont 450 cultivables, fut lente au début. Après l'asséchement des marécages du centre de la cuvette (1933), la superficie des cultures irriguées progresse de 2.000 ha en 1942 à 9.000 environ en 1955.

Mais dès 1942, l'établissement d'un premier bilan hydrologique provisoire (2 m³/s environ) fit entrevoir que la nappe-phréatique ne permettra pas d'irriguer plus de 1/10 à 1/5 de la superficie cultivable et cette étude (3) accélèrera la mise en chantier des travaux de dérivation des eaux de l'Oued Moulouya (4).

L'étude hydrogéologique amorcée en 1942 a été pousuivie depuis, notamment pour prévoir les réactions de la nappe au moment de l'irrigation intensive de la plaine. Et aujourd'hui, alors que les eaux superficielles commencent à irriguer les premiers secteurs à l'Ouest de la plaine des Triffa, les données climatologiques, hydrologiques et piézométriques recueillies au cours de ces 15 années permettent, dans le cas présent d'une plaine bien délimitée et déjà assez développée, d'établir un bilan plus précis qu'en 1942 quoique assez peu différent globalement.

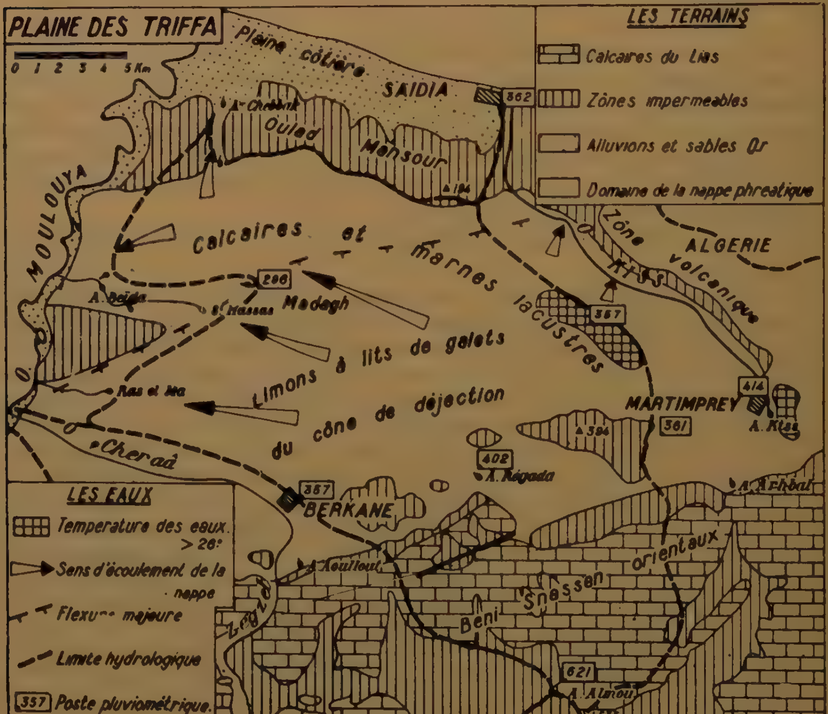


Fig. 1 — Schéma cartographique de la plaine des Triffa.

b) *Principales données hydrogéologiques.*

La plaine des Triffa (altitude moyenne : 75 m), est située entre la mer Méditerranée au Nord et les Monts des Beni Snassen au Sud (calcaires liasiques sur schistes primaires à l'Est — Marnes, grès et calcaires du Jurastique supérieur à l'Ouest — point culminant : 1535 m).

1) *La morphologie des Triffa* (voir figures 1 et 2) est le résultat d'un comblement marin au Négoène puis lacustre et alluvial au Villafranchien et au Quaternaire s.s. ainsi que de diverses influences tectoniques récentes — les marnes miocènes et pliocènes, se relèvent en bordure de mer, en un bourrelet de collines dites des « Oulad Mansour » (point culminant : 194 m). Ces collines taillées en « falaise morte » par une transgression marine du Quaternaire récent [5] séparent la plaine des Triffa de la plaine côtière de Saïdia, tant du point de vue climatique qu'hydrologique. Au Sud de ces collines, une ligne de flexure post-villafranchienne divise la plaine elle-même en 2 compartiments : au Nord et à l'Est, des marnes et calcaires lacustres villafranchiens moins perméables dans l'ensemble que les limons à lits de galets du Quaternaire s.s. qui au Sud et au centre de la plaine constituent un ancien cône de déjection très surbaissé.

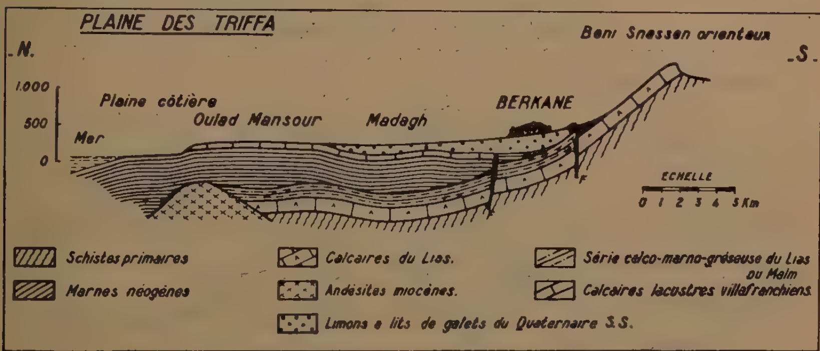


Fig. 2 — Coupe géologique schématique.

2) *L'hydrogéologie* de la plaine est « dirigée » par la stratigraphie et la structure sommairement décrites ci-dessus :

Une nappe phréatique existe dans les limons et calcaires lacustres du Quaternaire s.l.; son substratum imperméable est constitué par les marnes miocènes et pliocènes. La carte des courbes isopiézométriques de cette nappe [6] fait d'une part apparaître avec netteté la différence de perméabilité entre les limons et l'ensemble marno-calcaire lacustre et montre d'autre part que les zones d'alimentation sont situées au Sud et au Sud-Est de la plaine, les zones d'exurgence principalement à l'Ouest vers la Moulouya et dans une faible proportion au Nord-Est vers le Kiss et au Nord-Ouest vers la plaine côtière par la trouée de l'O. Chebbag.

Deuxième fait hydrogéologique important à noter : l'eau d'un certain nombre de puits alignés suivant une direction SE — NW présente une température de 7 à 10° supérieure à la température moyenne des eaux de la plaine. Cela fait soupçonner une alimentation de la nappe phréatique par une nappe profonde, suivant une ligne de faille. Cette nappe profonde est très probablement liée aux calcaires liasiques qui affleurent largement sur le flanc Nord des Beni Snassen orientaux et dont 4 sources principales situées au contact de la plaine indiquent le caractère très aquifère.

Enfin, la zone centrale de la plaine n'étant pas drainée par suite de la disposition tectonique décrite plus haut et d'une tendance subsidente probable jusqu'au Quaternaire moyen, les eaux qui ruissellent sur une large partie des Beni Snassen s'infiltrent dans leurs cônes de déjection en arrivant en plaine et alimentent ainsi la nappe phréatique.

* * *

II — Le bilan de la nappe phreatique des Triffa

Pour l'étude du bilan de la nappe des Triffa, nous la limiterons à sa partie riche et bien connue, soit une zone de 250 Km² environ, bordée au Sud par les Beni Snassen et l'Oued Cheraa à l'Ouest par la Moulouya, au Nord par les collines des Oulad Mansour, à l'Est par l'Oued Kiss.

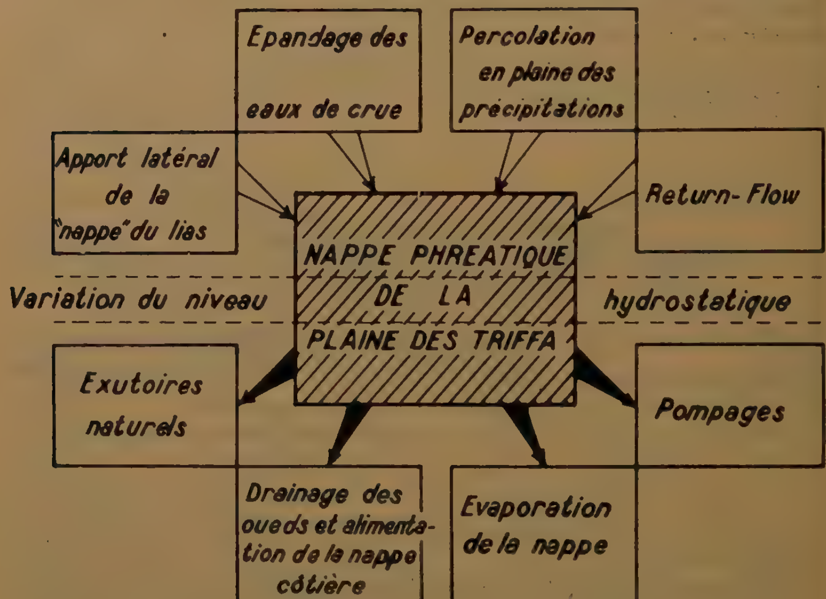


Fig. 3

Le schéma ci-dessus montre les différents éléments à considérer pour l'établissement du bilan de la nappe phréatique des Triffa, tels que'ils ressortent de l'étude hydrogéologique.

A) *L'ACTIF DU BILAN : les apports à la nappe.*

1) *Infiltration sur la plaine elle-même.*

L'étude des variations du niveau piézométrique des puits-témoins montre que l'alimentation de la nappe se fait en partie par la percolation des précipitations sur la plaine elle-même.

Pour approcher le coefficient d'infiltration, nous avons choisi d'appliquer à notre objet la méthode climatologique définie par Thornthwaite ([7] et [8]).

Malgré les critiques qui lui ont été faites par des hydrologues ([9]), cette méthode nous permet de tenir compte, dans l'étude du phénomène d'infiltration, de l'époque où se produisent les précipitations et de leur concentration — c'est un progrès par rapport à la pratique d'appliquer un coefficient d'infiltration uniforme et arbitraire à la moyenne des précipitations.

Voici d'après Présiozi ([10]) le principe de la méthode :

« La connaissance de l'évapotranspiration potentielle (E.P.) et de la pluviométrie permet de calculer le bilan hydrologique d'une région déterminée. Ces deux éléments climatiques sont totalement indépendants et leur variation au cours de l'année est très différente. Quand les précipitations sont supérieures à l'E.P. une certaine quantité d'eau est emmagasinée par le sol jusqu'à saturation; le surplus ruisselle ou s'infiltre profondément, c'est ce que les hydrologues appellent « l'écoulement ». Dès que les précipitations deviennent inférieures à l'E.P. le sol restitue l'eau emmagasinée, l'évapotranspiration réelle (E.R.) reste égale à l'E.P. jusqu'à l'épuisement de cette réserve puis elle devient inférieure à l'E.P. et égale à la pluviométrie ».

L'évapotranspiration potentielle mensuelle c'est-à-dire « la quantité d'eau requise mensuellement pour contrebalancer l'évaporation sur le sol et la transpiration par les plantes » (Joly), a été calculée pour Berkane avec des moyennes mensuelles de température établies sur 8 ans. (voir tableau ci-dessous).

TABLEAU I

BERKANE — Latitude 34°66

mois	S	O	N	D	J	F	M	A	M	J	J	A	Total
t	24,4	20,6	17,0	13,5	11,7	12,9	15,1	16,5	18,3	22,9	26,2	27,1	18,9
E.P.	118	78	48	29	23	27	44	57	77	120	161	162	946

t = température moyenne du mois en deg. centigrade
E.P. = évapotranspiration potentielle.

Malgré le caractère arbitraire du chiffre de 100 m/m proposé par Thornthwaite comme quantité de pluie nécessaire à la saturation du sol, nous avons conservé ce chiffre pour les Triffa :des observations de remontée de nappe (8 à 10 cm) le lendemain d'une période de 3 jours de pluie (128 à 188 mm suivant les points) intervenant au mois de mars 1957 (E.P. 44 mm) alors que la réserve du sol était nulle, tendent à faire considérer le chiffre de Thornthwaite plutôt comme un maximum dans le cas présent.

Ci-dessous à titre d'exemple le tableau du bilan hydrologique pour l'année-agricole 1954-1955.

TABLEAU II

	p	e.p.	b	e.r.	r	S
S	18	118	—100	18	0	0
O	6	78	— 72	6	0	0
N	18	48	— 30	18	0	0
D	97	29	+ 68	29	68	0
J	115	23	+ 92	23	100	60
F	49	27	+ 22	27	100	22
M	66	44	+ 22	44	100	22
A	96	57	+ 29	57	100	29
M	10	77	— 67	77	33	0
J	22	120	— 98	55	0	0
J	1	161	—160	1	0	0
A	0	162	—162	0	0	0
TOTAL	488	946		355		133

p = précipitations mensuelles mesurées en mm à Berkane (représentatives de l'ensemble de la plaine).
e.p. = évapotranspiration potentielle mensuellle calculée en mm pour Berkane (voir tableau 1).
b = bilan hydrique = p — ep.
e.r. = évapotranspiration réelle (= p pour les mois secs, et ep pour les mois humides).
r. = quantité d'eau (en mm) retenue par le sol en rétention jusqu'à un maximum de 100 mm (saturation) puis rendue pour l'évapotranspiration pendant les mois secs.
s. = surplus du bilan hydrique, en mm.

— La plus grande partie de la plaine des Triffa (telle qu'elle a été définie plus haut) n'ayant pas de drainage superficiel, on peut admettre que le « surplus du bilan hydrique » s'infiltre en totalité pour aller recharger la nappe aquifère. Donc en 1954-1955, sur une superficie de plaine de 250 Km² où l'infiltration est possbile, il y a eu un apport à la nappe par percolation des précipitations sur la plaine elle-même de 1050 l/s.

— Le même calcul que ci-dessus effectué pour chaque année de la période de 40 ans 1917-1957 montre qu'il n'y aurait eu d'infiltration sur la plaine qu'au cours de 16 années. La hauteur moyenne infiltrée pour cette période est de 23 mm soit un coefficient d'infiltration moyen de 6,3 %. L'irrégularité des infiltrations mise ainsi en évidence qui, sans l'apport allogène de la nappe des calcaires du Lias, ne permettrait pas le maintien d'une réserve souterraine permanente, justifie le classement de la plaine des Triffa dans la zone semi-aride [8].

Pour la période de référence 1951-1955 (entre les deux derniers relevés piézométriques de la nappe), on aboutit à un chiffre moyen annuel de 64 mm (coefficient d'infiltration = 15 %) soit un apport moyen annuel à la nappe de 500 l/s.

b) *Infiltration en plaine des eaux de ruissellement du massif montagneux.*

Il faut distinguer d'une part les bassins versants des oueds Kiss et Cheraa et d'autre part ceux des thalwegs dont le lit se perd en plaine.

La superficie totale en montagne de ces derniers est de 80 Km^2 et la moyenne des précipitations reçues est 45×10^6 m^3/an.

La majeure partie de ce bassin étant de nature très perméable (calcaire), seules les très grosses pluies apportent en plaine un débit estimé à 6×10^6 m^3/an; la moitié de ce débit de ruissellement doit s'infiltrer en plaine puisque les périodes de ruissellement correspondent en général avec celles où les évaporations sont les plus faibles : par épandage sur les cônes de déjection de ces thalwegs il s'infiltre donc environ 100 l/s.

L'apport latéral à la nappe phréatique des deux rivières plus importantes citées plus haut, est considéré comme très faible par suite de leur position excentrique en plaine et parce qu'elles ont plutôt tendance à drainer la nappe.

c) *Alimentation souterraine à partir de la « nappe » profonde des calcaires du Lias des Beni Snassen orientaux.*

La superficie des massifs calcaires qui par leur disposition tectonique peuvent participer à l'alimentation de la plaine des Triffa est d'environ 200 Km^2.

Ils sont considérés comme très perméables ([11]). Par analogie avec l'étude très précise faite en Tunisie pour la percolation sur le Djebel Zaghouan ([12]) dans des conditions de climat (altitude, latitude) et de terrains (calcaires du Lias dans les deux cas mais pente un peu plus forte ici) très comparables, on prendra un coefficient d'infiltration de 40 % pour la pluviométrie d'une station située au pied du massif montagneux (Aïn Regada : 402 mm), soit environ 30 % des précipitations tombées sur l'ensemble du massif calcaire. Il faut noter que cette méthode valable pour une période de pluviométrie moyenne, ne l'est plus, si on veut faire un contrôle hydrologique annuel de la nappe car le coefficient d'infiltration est variable suivant la concentration des pluies.

Néanmoins pour la période considérée ici (1950-1955) on peut admettre qu'il s'est infiltré en moyenne sur les calcaires des Beni Snassen une quantité d'eau annuelle de 32×10^6 m^3/an soit 1 m^3/s.

Or, bien que les jaugeages aient été peu fréquents et que l'indice de variabilité soit élevé ([13]), on peut valablement estimer que le débit total des sources du flanc Nord des Beni Snassen oscille autour de 300 l/s. Un apport de 700 l/s à la nappe des Triffa est donc théoriquement possible : la structure tectonique révélée par la géophysique et la carte des températures le rendent quasi-certain. Il reste à savoir si la totalité de cette réserve profonde profite à la nappe phréatique ou si une partie alimente des sources en mer : ce que nous connaissons de l'océanographie de la plate-forme littorale entre Cap de l'Eau et Port-Say ([14]), ainsi que les épaisseurs de marnes néogènes révélées par géophysique et sondage au Nord des Triffa rendent ces sources improbables ou très peu importantes (sous des charges condisérables.)

d) *Réinfiltrations d'eau d'irrigation*

On verra plus loin que la quantité d'eau nécessaire pour l'irrigation des 9.000 ha de terres mises en valeur est de 1,7 m^3/s.

Si l'on applique la méthode de Thornthwaite pour déterminer le pourcentage d'eau réinfiltrée (en remplaçant dans l'expression du bilan hydrique les précipitations par la somme des précipitations et des quantités d'eau d'irrigation) on arrive à un

chiffre de réinfiltration de 535 l/s soit 31 %. Or des expériences précises faites dans le Haouz et le Tafilalet (plaines du Sud marocain) ont mis aussi en évidence un coefficient de réinfiltration de 30 %. C'est également l'ordre de grandeur du « return-flow » admis par les auteurs américains.

B) — *LE PASSIF DU BILAN*

Ce sont : les pompages,
— les exutoires et l'alimentation latérale d'autres nappes.
— l'évaporation de la nappe dans les zones d'affleurement.

a) *Les prélèvements par pompage* : c'est un des chapitres les plus difficiles à analyser correctement : les utilisateurs n'étant pas à même de préciser combien ils pompent.

On compte actuellement environ 400 puits équipés de pompe représentant une capacité de pompage installée de 8 m³/s. Mais il est bien évident que ce chiffre est de loin supérieur au pompage réel : d'une part le prix de revient de l'énergie (environ 2 francs le m³ pompe — moyenne calculée sur 18 stations de pompage du centre de la plaine) ne permet pas de pomper économiquement pour l'irrigation à plus de 40 m et le nombre de stations de pompages importantes doit être ainsi un peu réduit; d'autre part le pompage pour l'irrigation est une opération essentiellement discontinue.

Le chiffre réel de pompage peut être approché par la considération des superficies irriguées (chiffres fournis par le Service des Impôts Ruraux) et des modules d'irrigation des différentes cultures tels qu'ils sont admis par le Génie Rural ([15]).

TABLEAU III

Cultures	Nbre. d'ha.	Modules en l/s/ha.	Total m³/s.
Vignes	3.800 ha	0.11	0.42
Agrumes	3.000 ha	0.32	0.96
Cultures maraichères	2.200 ha	0.45	0.99
TOTAL	9.000 ha	0.26	2.37 m³/s.

Mais la considération des chiffres très précis du Secteur de Modernisation du Paysannat (pour 620 ha de cultures surtout maraîchères avec un peu de céréales et quelques arbres fruitiers le module moyen est de 0,15 l/s/ha) nous amène à considérer les modules retenus par le tableau III comme un peu trop élevés.

Le module moyen annuel *mesuré* pour les périmètres irrigués d'Algérie (qui représentent assez bien les conditions moyennes des Triffa) nous donne un autre élément d'appréciation : 6.000 m³/ha/an pour une année à pluviométrie moyenne. En appliquant ce chiffre au périmètre irrigué actuellement dans les Triffa, on aboutirait à un débit global moyen de 1720 l/s. Or il y a 2.500 ha irrigués par gravité soit au pied des Beni Snassen (sources des calcaires du Lias) soit aux exutoires de la mappe.

Donc les prélèvements par pompage se réduiraient à : 1.240 l/s. Mais un dernier élément (la considération des factures d'énergie électrique qui concernent la moitié environ des stations de pompage de la plaine) nous amène à relever ce chiffre à 1.500 l/s.

b) *Les exutoires naturels*

Les sources (Ras el Ma, Sidi Hassas, A. Beida, à l'Ouest, drainage par l'O. Kiss à l'Est) ont des débits très variables au cours de l'année et au cours des années. Mais leur débit moyen peut être chiffré à 350 l s. Les apports souterrains à la nappe des alluvions de la Moulouya et à celle des sables de la plaine côtière sont très réduits à cause de la structure de la plaine qui diminue beaucoup les possibilités d'abouchements — Estimons-les à 75 l/s en première approximation.

c) *L'évaporation de la nappe* : Elle devait être très importante autrefois avant l'asséchement des marécages du centre-Ouest de la plaine par drainage, et aussi avant l'abaissement de la nappe par suite des pompages intensifs. Aujourd'hui la surface où elle est théoriquement possible est très faible :

— Zone où la nappe est à moins de 5 m = 3 à 4 Km2

— Zone où la nappe est à moins de 10 m = 20 à 25 Km²

La nature assez argileuse des limons de surface et le climat relativement tempéré ne permettent pas à notre sens d'évaporer plus de 50 l/s.

C) *CONCLUSION*

Maintenant qu'ont été estimées les différents chapitres du bilan nous allons comparer l'actif et le passif pour la période 1951-1955, c'est-à-dire entre deux « relevés » piézométriques complets de la nappe.

Apports à la nappe		Sorties de la nappe	
1) Percolation en plaine des précipitations =	500 l/s	1) Pompages =	1.500 l/s
2) Epandage des eaux de crue =	100 l/s	2) Exutoires naturels =	350 l/s
3) Apport latéral de la nappe du Lias. =	700 l/s	3) Drainage des oueds et alimentation latérale de la nappe côtière =	75 l/s
4) « Return flow » =	535 l/s	4) Evaporation de la nappe	50 l/s
TOTAL =	1.835 l/s		1.975 l/s

Or la nappe accuse pour cette période une baisse moyenne de 2 m et le coefficient d'emmagasinement des terrains aquifères de la plaine calculé à la suite d'essai de pompage est de l'ordre de 3 % ce qui représente sur l'ensemble de la plaine un « déficit » global de 15×10^6 m³; ce volume équivaut assez bien au déficit que met en évidence le bilan : 140 l/s × 5 ans soit 22×10^6 m³. Cette concordance justifie par elle-même les évaluations et les approximations que le manque de mesures précises et suivies oblige à faire en certains domaines.

* * *

Pour un contrôle hydrologique de la nappe, il y aurait certainement lieu :

a) de préciser les infiltrations sur la plaine par des études sur cases lysimétriques ou par une méthode comme celle de Turc [16] qui tient compte de la végétation et qui en prenant une base de 10 jours (au lieu d'un mois) tient mieux compte que celle de Thornthwaite de la concentration des précipitations.

b) de préciser les infiltrations sur les calcaires, par exemple par une expérience de jaugeage des sources qui sourdent d'un massif « perché ».

c) de préciser les « sorties » de la nappe des calcaires (sources du pied des Beni Snassen) et de la nappe phréatique (exutoires) par des jaugeages aussi fréquents au cours de l'année que les relevés piézométriques.

d) de préciser les prélèvements par pompages en effectuant des enquêtes auprès des utilisateurs.

Mais il est certain qu'il restera toujours des facteurs qu'on ne pourra qu'évaluer — évaporation de la nappe, alimentation latérale d'une nappe par une autre... Cependant dans certains cas, ces facteurs peuvent être considérés comme nuls ou très petits

— Dans le cas des Triffa, un tel contrôle hydrologique de la nappe sera nécessaire dès que commencera l'irrigation de secteurs situés à l'amont phréatique c'est-à-dire à proximité des zones d'alimentation. Car il est certain que la suppression des pompages d'une part, et l'augmentation sensible des débits de « return flow » d'autre part vont rompre l'équilibre actuel — le niveau de la nappe remontera et le débit «sorti » par évaporation ainsi que le débit des exutoires naturels augmenteront. Or la capacité d'exhaure de ceux-ci est sans doute limitée si on considère l'existence de marécages à une époque où les pompages étaient peu importants. Pour éviter la recréation de tels marécages, les services chargés de la mise en valeur doivent prévoir un drainage classique ou mieux un drainage par stations de pompage d'Etat judicieusement placées.

BIBLIOGRAPHIE

(1) Ambroggi R. — Premier essai de bilan des eaux souterraines du Maroc — *Bull. Soc. Sc. Nat.* Maroc (1955).

(2) Louis Gentil — L'Amalat d'Oujda — *Bulletin de la Soc. de Géographie* — 1911.

(3) Rampont — Note inédite — Archives du C. E. H. — Rabat.

(4) Molin — La plaine des Triffa — *Revue Travaux* — Fév. 1955.

(5) Gigout, Mortier, Raynal — C. R. Som. Soc. Géol. Fr. 1957.

(6) Mortier F. — Présentation de la carte de la nappe phréatique des Triffa — Congrès U. G. G. I. de Toronto (1957).

(7) Thornthwaite — An Approach toward a rational classification of climate. *Géophysical Review* — New-York (1948).

(8) Joly — Les milieux arides — définition — extension — Notes marocaines de géographie 1957.

(9) Serra — Le contrôle hydrologique d'un bassin versant, C. R. des 3mes journées de l'Hydraulique Alger (1954) p. 29.

(10) Presiozi — Le climat de la Tunisie — Evapotranspiration Bilan hydrologique — Zones climatiques — idem p. 81.

(11) H. Faure — Hydrogéologie de la région d'Aïn Regada — Diplôme Fac. Sc. Paris 1950.

(12) Tixeront & Berkaloff — Bilan d'eau des massifs calcaires en Tunisie — *UGGI* — Bruxelles 1951.

(13) Stretta — Hydrogéologie du flanc Nord des Beni Snassen *N. et M. du Serv. Géol. du Maroc*, n° 71 — 1950.

(14) J. Bourcart, L. Glangeaud — Morphotectonique de la marge continentale Nord-Africaine — *BSGF*, T. IV p. 751.

(15) Dutard — Contribution à l'étude de la mise en valeur des Triffa. Rabat 1949.

(16) Turc — Le bilan d'eau des sols — relations entre les précipitations, l'évaporation et l'écoulement — C. R. des 3me journées de l'Hydraulique — Alger (1954) p. 36.

ESTIMATING QUANTITY AND QUALITY OF GROUND WATER IN DRY REGIONS USING AIRPHOTOS

JOHN F. MANN, Jr.
Department of Geology University of Southern California
Los Angeles 7, California

Abstract

Under certain circumstances it is possible to determine from airphotos alone where water may be obtained in arid and semi-arid regions, the minimum amount that is perennially available, and whether the water is of good chemical quality. The interpretation is based on the simple premise that water of good quality which is forced to the surface in dry regions will have been pre-empted by phreatophytes, and that the amount of water available will depend upon the size of that vegetated area. Some familiarity with the general region and the plant types may be necessary to interpret with maximum effectiveness. The geologic condition attending the appearance of the water at the surface may be evident on the airphoto. A fault acting as a conduit will show springs where it intersects the axes of the valleys. A small spring produces a spot of phreatophytes, whereas a larger spring will show a line of phreatophytes extending downstream. A fault acting as a barrier is shown by a patch of phreatophytes sharply limited by the fault on the downslope side, and commonly a strip of dense vegetation marking the overflow. Areas of constriction in dry alluvial channels are often marked by large quantities of rising water. In closed desert basins with no groundwater outlet, the two areas of alluvial fans discharge large quantities of water; a concentric strip of phreatophytes is replaced downslope by halophytes where salinity has been increased by a high evaporation rate.

Although the examples discussed are in western United States, the same approach may be applicable in other dry regions.

Introduction

Since 1950, various members of the Department of Geology, University of Southern California have been directing their major research efforts toward problems of desert geology, with particular emphasis on eastern and southeastern California. One of the important problems investigated has been the availability of potable water supplies; the purpose of this paper is to outline briefly the preliminary results of the continuing study of the use of airphotos in the location and evaluation of water supplies in desert areas.

The chief basis for interpreting the airphotos is an understanding of the significance of the various plant patterns. Desert surfaces characteristically appear pale on airphotos, whereas the plants are almost always dark gray to black. On the unvegetated surfaces the plants can not grow because of lack of soil, excessive salinity, or other unfavorable conditions. The xerophyte patterns are indicative of plants adapted to utilize sparse infrequent rainfall; they denote that no shallow ground water is present. Halophytes overlie shallow ground water, but water which is too saline to be potable. True ground-water plants, the phreatophytes, indicate the presence of ground water at shallow depths. Most types of phreatophytes utilize water which is potable, although some may be found tapping water of excessive salinity.

Unvegetated Surfaces

In the California deserts, surfaces devoid of vegetation constitute but a few per cent of the total arid area. Several distinct types may be recognized.

Bare-rock Surfaces. On bare-rock surfaces, where slopes are too steep to permit the development of a soil mantle, plants are scarce. Although no shallow waters may be present, the detection of a line of xerophytes developed on a soil marking the position of fault gouge may be a guide to deeper waters trapped along or behind this fault. Even if not accentuated by vegetation, well developed joint planes in plutonic rocks may offer excellent objectives in prospecting for deeper water.

Dry-type playas. Playas underlain by low water tables are shown on airphotos by pale unvegetated areas of uniform tone. Dry-type playas are probably confined to ground-water basins in which there is discharge by subsurface flow but none by evapotranspiration. The absence of vegetation may be the result of impermeable soil, excessive salinity, or both. The xerophyte pattern of the adjoining alluvial fans ends abruptly at the edge of the playa; there are no intermediate bands or strips of differing vegetation. The absence of vegetation bands, coupled with the uniform pale color tone, serves to differentiate the dry-type playas from the moist-type playas.

Dunes. Large areas of sand dunes generally have no perennial plants except near the edges. Water may be available beneath dunes, either as perched water in the base of the dune sand, or as a shallow water table entirely beneath the dune sand in the underlying deposits. Near the central parts of the large dune areas the water table is usually more than 50 feet deep, and beyond the reach of phreatophytes. The plants which suddenly grow on desert dunes following heavy rains are small, pale-colored, and would only rarely be detected on airphotos.

Xerophyte Patterns

Most plants which grow in desert regions are independent of perennial water supplies. These xerophytes have a wide spacing and an extensive shallow root system

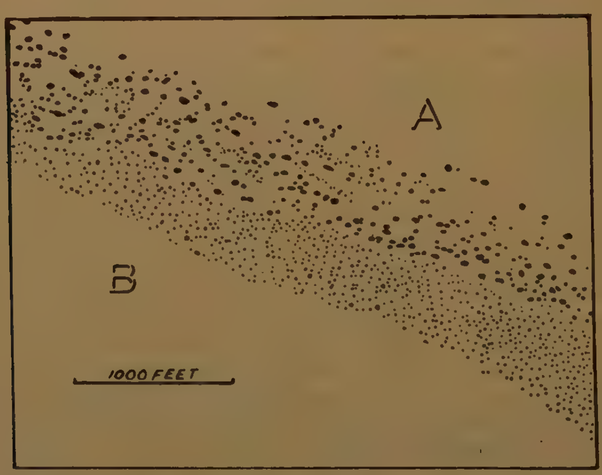


Fig. 1 — Tracing of airphoto showing contrast between dry-wash xerophyte pattern (A) and sheet-wash xerophyte pattern (B).

to utilize effectively the sparse and infrequent rainfall. Between rains the plants become dormant. That lack of water is a controlling factor is shown by the vigor with which these xerophytes grow when favorably situated, as along roads and flood control ditches.

Sheet-wash xerophyte pattern. On alluvial fans the xerophytes benefit from direct rainfall and also from small volumes of semi-channeled flow. This shotgun-type pattern can be discerned on airphotos with a scale of 1 : 20,000, but can be studied better on the larger scales (fig. 1). Most alluvial fans will show remnants of a darker surface a few feet higher than the abundant anastomosing channels. The xerophytes are smaller and sparser on this higher surface than in the lower, paler washes.

Desert-flat xerophyte pattern. On the flattest alluvial surfaces, where there is little runoff, the xerophytes are smaller than on the alluvial fans. These plants are stunted because they must subsist on direct rainfall only, and on clayey soils much of this rainfall is evaporated directly. On the sandier portions of the desert flats, the xerophytes are more vigorous, perhaps reflecting that more of the rainfall can be utilized by the plants.

Dry-wash xerophyte pattern. The more or less diffuse runoff on the alluvial fans is eventually channeled into broad sandy washes, where the larger intermittent supplies of water are reflected as larger xerophytes. On airphotos, dry washes are usually of a paler color than the remainder of the alluvial fan. The size of the dry-wash trees is a rough index of the thickness of the clean alluvium in the wash and of the amount of water available to the plants. For a short while following floods potable water may be obtained at shallow depths in these washes. However, the thalweg usually has a steep gradient and the water rather quickly drains downslope. The dry-wash xerophytes become dormant as soon as they have depleted the water films on the sand grains.

Linear xerophyte patterns. Superimposed on the random xerophyte patterns on alluvial surfaces or on hills of older materials may be seen prominent linear trends of xerophytes following the outcrops of faults. A tracing of an airphoto showing such an occurrence is presented in fig. 2. The faults are in a hill of cemented alluvial deposits a few miles northeast of the well-known San Andreas Fault zone and are related to it in trend. The plants are not phreatophytes but are vigorous xerophytes thriving in gouge soil.

Fig. 2 — Tracing of airphoto showing faults delineated by xerophytes.

SURFACES UNDERLAIN BY SHALLOW SALINE WATERS

The most obvious areas of shallow saline waters in the California deserts are the bottoms of closed topographic basins occupied by moist-type playas. It is likely that the subsurface basins are also closed and that discharge of water from the basin is primarily by evapotranspiration. In sharp contrast to the uniform color tone of the dry-type, the moist-type playa on airphotos shows a splotchy pattern of numerous shades of gray from very pale to very dark. On some moist-type playas a well-developed polygonal pattern may be evident. In the central parts of moist-type playas there is no vegetation, but on the edges there is usually a strip of halophytes marking a transition zone between the brines of the playa and the fresher waters at the toes of the alluvial fans (fig. 3). The banded pattern flanking the splotchy playa surface is highly diagnostic of a basin in which the shallow ground waters have been made highly saline by excessive evaporation.

Fig. 3 — Tracing of airphoto showing moist-type playa (A), halophyte strip (B), and alluvial fan (C).

SURFACES WHICH MAY BE UNDERLAIN BY SHALLOW POTABLE WATERS

Direct evidence of effluent groundwater or shallow water tables is to be looked for in plant patterns other than those of the xerophytes. The appearance of phreatophytes on airphotos is usually as dark gray to black spots, often arranged in a somewhat systematic manner. The coarser-textured phreatophyte patterns can be clearly discerned on airphotos with a scale of 1:62,500, about the smallest scale commonly flown commercially. It is axiomatic to the present study that phreatophytes will have pre-empted all the water of tolerable salinity that is within a few feet of the ground surface, and some of the water from greater depths. It was established some time ago by Meinzer (1927) that most phreatophytes are able to utilize water within a few feet of the ground surface and that some, such as mesquite (*Prosopis*) tap water tables which are 50 feet or more below the ground surface. The amount of water being used by the phreatophytes (which can be considered the minimum amount that

can be salvaged for human purposes) is determined by multiplying the area of phreatophytes by the unit consumptive use. Depending on the type of phreatophyte, the unit consumptive use shows a wide range, from about 3 to about 10 acre-feet per acre per year. A one-acre patch of phreatophytes would require a minimum of one million gallons of water per year, and probably much more.

As an aid in recognizing the appearance of phreatophytes on airphotos, a classification of the patterns will be presented, along with diagrams traced from actual airphotos. In addition, some data on the geology and hydrology of the various patterns will be included.

Point Phreatophyte Patterns.

Point discharges of ground water at the surface are called springs. for which there are numerous geological explanations. In desert areas these springs are invariably marked by phreatophytes with an areal extent dependent upon the flow of the spring. Where the spring exits along a fault, quite often the trace of the fault is evident on the airphoto. In large dune areas, especially near the periphery of the sand mass, a shallow water table may be tapped by lone phreatophytes or by small groups of phreatophytes in the hollows (fig. 4).

Fig. 4 — Tracing of small-scale airphoto showing dune ridges and phreatophytes in hollows.

Linear Phreatophyte Patterns

More often than not, a fault along which a single spring appears, will be the locus of a series of springs. In fact, on airphotos such a spring line may be the most useful feature for detecting or confirming a fault. If the flow of a spring is large, a pronounced line of dark vegetation extending downstream is supported by the effluent water. Where a fault acts as a ground-water dam, it may appear on airphotos as a nearly continuous line of seepage. Such an occurrence, traced from an airphoto taken along the San Andreas Fault Zone, appears in fig. 5. The seepage line is limited abruptly on the down-gradient side and is scalloped as a result of re-entrants on the up-gradient side. Another line of phreatophytes marks the canyon where the

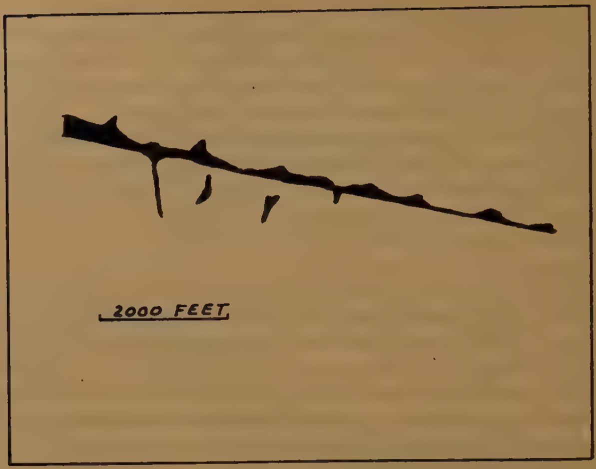


Fig. 5 — Tracing of airphoto showing lines of phreatophytes along San Andreas Fault Zone, California.

water spills across the barrier block. In another part of the San Andreas Fault Zone, where Recent alluvium has been dammed, the same two linear patterns can be detected, but are more obscure (fig. 6).

Fig. 6 — Tracing of airphoto showing phreatophytes in area of shallow water created through damming of Recent alluvium by San Andreas Fault Zone, California.

Strip Phreatophyte Patterns

Fan-toe phreatophyte strips. In the lower parts of alluvial fans, where the water table is close to the ground surface, there may be a broad strip of phreatophytes

Fig. 7 — Tracing of airphoto showing fan-toe phreatophyte strip.

Fig. 8 — Tracing of airphoto of Furnace Creek alluvial fan, Death Valley, California, showing unusual phreatophyte pattern.

(fig. 7). In such strips, especially in the upslope portions, there is a good chance of obtaining large quantities of potable water at shallow depth. A unique modification of the fan-toe phreatophyte strip is shown in fig. 8. This is in Death Valley, where the Furnace Creek alluvial fan has been deposited on impervious lake beds. This unusually well-watered fan has a fault spring near its apex. Spring flow and runoff can travel downward no farther than the impervious lake beds, then must move downslope and appear as seepage at the fan toe. Beyond the fan toe, excess water percolates radially outward as subterranean flow in the alluvium deposited in channels out in the lake beds. The channel underflow is traced as numerous sinuous lines of phreatophytes arranged like the spokes of a wheel. Thus there is the arrangement of linear patterns to form an arcuate strip pattern.

Wadi phreatophyte strips. The nearest relative of the Saharan wadis in the California deserts is perhaps the Mojave River. It has a very large tributary drainage of high elevation feeding a long thick strip of alluvium which ends in a closed desert basin. There is continuous surface flow only in a few stretches associated with alluvial constrictions where the subsurface cross-section is insufficient to transmit all the water as underflow. Upstream from these constrictions are dense areas of phreatophytes covering the entire width of the alluviated valley. Downstream from some of the constrictions the river flows as a surface stream; downstream from others the water table drops quickly and there are no phreatophytes. Along certain reaches of the dry river bed, some of the deeper-rooted phreatophytes are abundant.

Perennial stream phreatophyte strips. Distinct from the wadis are large rivers such as the Nile and the Colorado which rise in regions of high elevation and rainfall, and carry large volumes of water across desert regions to the sea. Although these have continuous perennial flow, they are characterized by tremendous changes in the volume of flow. Because of evaporation from free water surfaces, and from the capillary fringe where the water table is close to the ground surface, the shallow ground waters often have a high salinity. Beneath the shallowest waters are usually large volumes of potable water.

Patchy Phreatophyte Patterns.

The largest and darkest-colored phreatophyte spots on airphotos of the California deserts are usually mesquite. Because of a long tap root which can go 50 feet and more, the mesquite can grow in many places where more shallow-rooted phreatophytes can not. Mesquite is very widespread and produces a characteristic patchy pattern due to an uneven distribution of the individual plots or groups of plants. On small dunes the mesquite may cover the entire sand surface and show as solid subcircular disks (fig. 9). As the dune increases in size, the mesquite dies in the central part of the dune, and the dark vigorous bushes are confined to the periphery of the sand patch (fig. 10).

Fig. 9 — Tracing of airphoto showing dunes completely covered by living mesquite.

Fig. 10 — Tracing of airphoto showing mesquite dune ringlets where living mesquite occurs only on periphery of dunes.

Problems of salinity determination on airphotos

The problem of estimating the salinity of water being used by phreatophytes, from a study of airphotos alone, is a difficult, though not impossible, one. First of all, the particular species of plant must be deintified from the airphoto. On scales of 1:20,000 and smaller,mesquite (*Prosopis*) may be type only the that can be recognized in the California deserts. On scales of 1:10,000 or larger, the identification of many other types is possible. Beyond identification, the salinity tolerance of the species must be known. Few phreatophytes are so intolerant of salinity that they grow only in potable water, although many are usually found associated with it. A considerable number of species tolerate a wide range of salinities, from potable water to 10,000 or more parts per million total dissolved solids. To resolve this part of the problem it will be necessary to accumulate statistical information on water salinity vs. plant species; this approach was used by Meinzer (1927). Fortunately, most phreatophyte occurrences which have been investigated were found associated with potable waters. In some instances, if the shallow waters prove to be saline, deeper drilling and casing off the shallow waters may result in waters of lower salinity.

Ground-water occurrence inferred through recognition of land forms

Many of the principles discussed in the preceding analysis of plant patterns on airphotos could be applied by a person with little knowledge of geology. For locating small supplies of water for emergency or temporary purposes, such an approach may be quite adequate. If larger, continuing supplies are desired, a more thorough geologic analysis of the airphotos is necessary. A geologist trained in desert hydrology can infer a great deal about deeper sources of water from the airphotos alone; such a study, logically following the approaches used in this paper, would be an effective prelude to the field study and test drilling which must follow.

REFERENCES

CLEMENTS, Thomas; MANN, John F. Jr.; MERRIAM, Richard H.; and STONE, Richard O. — 1955 — An evaluation of types and scales of aerial photographs for use in arid regions; A Research Report submitted to the United States Air Force by members of the staff of the Department of Geology, University of Southern California. Unpublished.

MEINZER, O. E. — 1927 — Plants as indicators of ground water; United States Geological Survey Water Supply Paper No. 577.

Note: As defined for the deserts of California, *dry-type playas* are those flat clayey surfaces of ephemeral lake bottoms associated with deep water tables, where the ground surface is well above the reach of the capillary fringe. On the other hand, *moist-type playas* are found where the water table is within a few feet of the ground surface; the capillary fringe reaches the ground surface and there is generally a salt crust overlying the permanently moist clays. *Halophytes* are specialized plants which can thrive where the soil moisture is of abnormally high salinity.

DETERMINATION DE LA QUANTITE D'EAU UTILISABLE A L'EXEMPLE D'UN RABATTEMENT DE LA NAPPE SOUTERRAINE DANS UNE REGION ETENDUE

Dr.-Ing. GÜNTHER NAHRGANG
Staattiche Ingenieurschule für Bauwesen Köln

RÉSUMÉ

Un bassin étendu est divisé par des failles parallèles en quelques massifs plus ou moins abaissés. A cause de l'exploitation minière, on a commencé à abattre la nappe dans l'un des massifs, dont l'inclinaison est normale à la direction des failles le limitant. Des sables et des graviers d'une épaisseur de 10 à 80 m forment le milieu poreux rempli d'eau qui doit être évacué jusqu'à la couche imperméable.

Du fait de l'inclinaison de la couche imperméable et à cause de plusieurs petites failles la traversant, l'épaisseur de la nappe varie de sorte que la possibilité de l'application des formules théoriques connues pour le calcul des puits n'est guère à envisager.

Pour étudier l'écoulement et pour déterminer la quantité d'eau de la nappe il faut plutôt se servir des observations exécutées pendant le rabattement.

Les méthodes utilisées pour l'examen des observations sont exposées en prenant l'exemple d'un important captage d'eau avec un débit extraordinairement grand. Déjà l'état naturel, c'est-à-dire avant le commencement du rabattement, la nappe est en mouvement. Ce mouvement est changé par le captage d'eau susmentionné. L'étude de l'accroissement du bassin d'alimentation en fonction du temps, ainsi que l'étude des différents facteurs qui influencent ce mouvement non permanent de la nappe rendent possible la détermination des grandeurs de la perméabilité k, de l'alimentation de la nappe et de la porosité utilisable du milieu poreux. Enfin, la connaissance de la porosité permet la détermination de la quantité d'eau utilisable de la nappe.

A. GÉNÉRALITÉS.

Dans une région étendue de l'Allemagne occidentale, on vient d'entreprendre un rabattement énorme de la nappe souterraine pour permettre l'exploitation de mines (1) (2) (3) (4) (5) *). C'est pourquoi on y a installé plusieurs captages d'eau. Les résultats d'observation obtenus dans la région de l'un de ces captages (suivant les données de (6)) vont être examinés dans ce qui suit. Il s'agit de trouver les facteurs essentiels du rabattement de la nappe pour pouvoir déterminer la quantité d'eau utilisable.

B. LA GÉOLOGIE DU TERRITOIRE.

Des failles parallèles orientées du sud-est au nord-ouest divisent un bassin étendu en quelques massifs plus ou moins enfoncés. Le rabattement susmentionné doit être exécuté dans l'un de ces massifs. Le massif a environ 14 km de largeur. La section fig. 1 (tirée de (4) et (7)) montre une couche imperméable d'argile s'inclinant de sud-ouest à nord-est, qui forme la partie inférieure d'une couche de sables et de graviers remplie d'eau qui atteint 80 m d'épaisseur. La fig. 2 montre la carte du bassin en question en même temps que la surface de la couche imperméable (tirée de (7).

(*) Les chiffres entre crochets renvoient à la bibliographie à la fin de l'article.

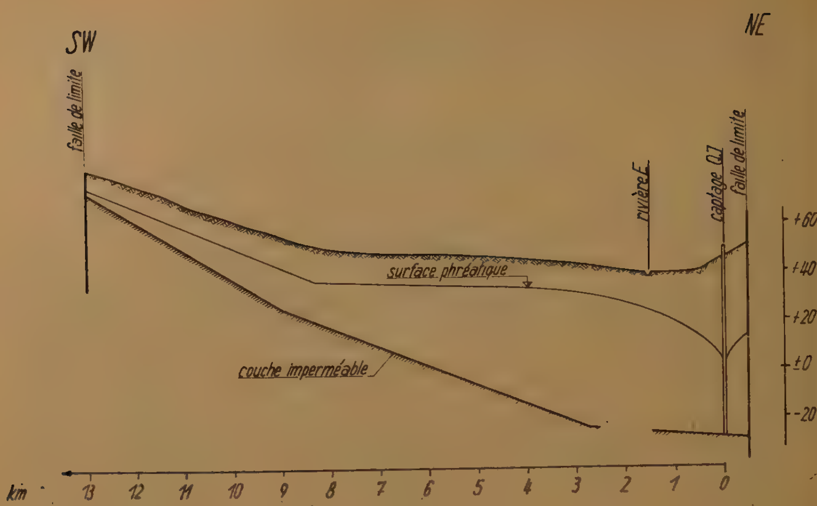

SW
NE
faille de limite
rivière E
captage Q7
faille de limite
surface phréatique
couche imperméable
+60
+40
+20
±0
-20
km
13 12 11 10 9 8 7 6 5 4 3 2 1 0

Fig. 1


36 40 44 48 52 56
50
46
42
38
34
30
26
22
18
±0
+50
28-12-56
Q7
26-5-56
28-12-55
+50
±0
+100
+100
+50
ligne de même hauteur de la couche imperméable
faille de limite
faille
limite du bassin d'alimentation
0 2 4 km

Fig. 2

En outre on y a dessiné de nombreuses petites failles existant à l'intérieur du massif ainsi que les failles principales susmentionnées qui limitent le bassin au sud-ouest et au nord-est.

La couche imperméable n'existe pas au voisinage de la limite entre les deux lignes en traits interrompus de sorte qu'il y ait ici une communication libre avec les couches inférieures remplies d'eau également et d'une épaisseur énorme.

Fig. 1 montre que la surface du terrain est aussi inclinée du sud-ouest au nord-est. Près de la limite à l'est la rivière E envoie parallèlement ses eaux au nord-ouest.

C. Le cours du rabattement et les méthodes pour l'examiner.

1) *L'état avant le commencement du rabattement. Possibilités d'un examen théorique.*

La fig. 3 représente la carte de la surface libre de la nappe avant le commencement de l'évacuation le 17-10-1955.

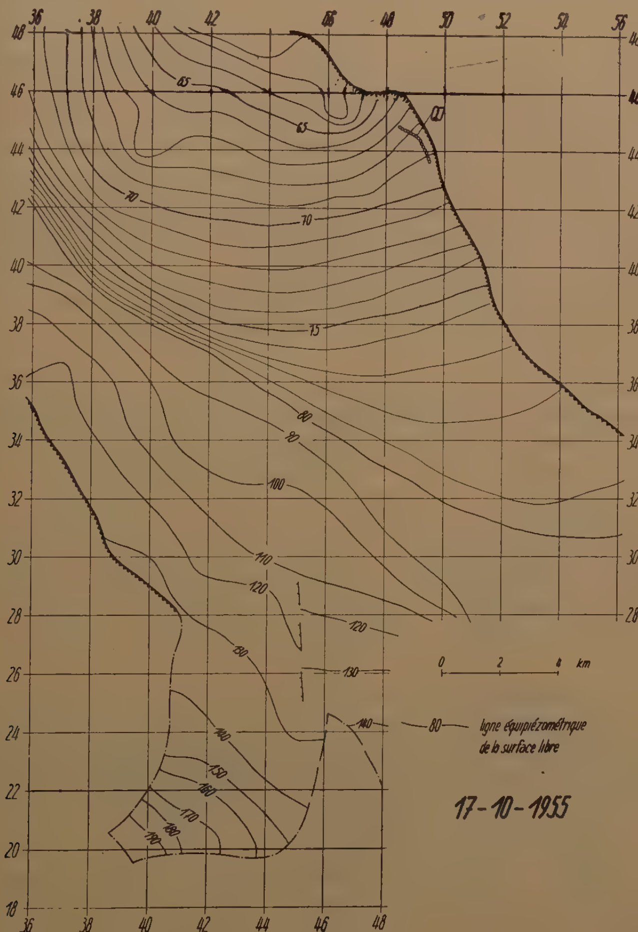


Fig. 3

C'est ce jour là qu'on inaugura le captage QI indiqué dans fig. 3, dont le rabattement sera examiné par la suite. On reconnaît qu'avant le commencement du rabattement déjà la surface libre de la nappe s'oriente de la limite sud-ouest du bassin vers la rivière E. Cet écoulement naturel a été déjà influencé avant l'exploitation du captage QI par des captages antérieurs. Il est aisé à concevoir une application de procédés théoriques pour l'examen hydraulique de captages de puits tels qu'ils ont été développés par exemple pour des écoulements non-permanent par Weber ([8]), Schneebeli ([9]) et autres. Mais en regeardant les cartes fig. 2 et 3, on reconnaît que, vu les circonstances tellement compliquées, il faut renoncer à des procédés théoriques.

2) *L'accroissement du bassin d'alimentation.*

Le débit maximum des puits de captage pendant la période du 17-10-1955 jusqu'au 31-12-1956 s'éleva à 5,6 m^3/s et le débit moyen pendant le même laps de temps à 3,7 m^3/s. Dans le bassin d'alimentation du captage QI, d'autres captages plus petits existent encore, dont le débit moyen se montait à 0,20 m^3/s.

Le bassin d'alimentation du captage QI est déterminé par des limites fixes et des limites mobiles (voir fig. 2). Il est borné par les failles de limite, au sud-est par la ligne de partage vers un autre captage d'eau, au sud-ouest par la deuxième faille de limite et au sud où cette faille disparaît, par une chaîne de montagnes. Selon les observations, les limites nommées jusqu'ici sont invariables. La limite au nord-ouest est mobile; elle est représentée par la ligne du partage des eaux vers un autre captage.

Supposons pour notre schéma, que cette limite soit une ligne droite qui se tourne autour d'un point situé un peu au nord-ouest du captage QI sur la faille de limite. Cette ligne droite et la faille de limite au nord-est forment le bassin d'alimentation ou l'éventail d'alimentation dont l'accroissement se fait par l'agrandissement de l'angle d'ouverture entre la faille nommée et la ligne droite. L'éventail d'alimentation est dessiné dans la fig. 2 et montre son développement à la fin de différentes périodes, tandis que le tableau suivant indique son accroissement:

TABLEAU 1

date	surface de l'éventail d'alimentation (km^2)
17-10-1955	0
28-12-1955	186
26- 5-1956	219
28-10-1956	251
28-12-1956	268

Les plans de différences du 30-6, 30-9 et 31-12-1956 montrent le rabattement de la surface libre de la nappe depuis le commencement jusqu'à la fin de différents stades. On y voit dessiné les lignes de mêmes différences de rabattement comparé à la nappe d'eau orignale (voir fig. 4).

3) *La carte de la surface libre de la nappe du 28-12-1956 et son examen.*

La carte avec les lignes de même hauteur de la nappe du 28-12-1956 est dessinée dans fig. 5.

Au moyen de celle-ci on a trouvé — entre autre — les limites de l'éventail d'alimentation à ce moment. Ce plan ainsi que les plans de différence (fig. 4) ont été utilisés pour analyser intensément l'écoulement du captage QI en admettant — et ici on s'approche probablement fort de la réalité — que la perméabilité k_f de la nappe

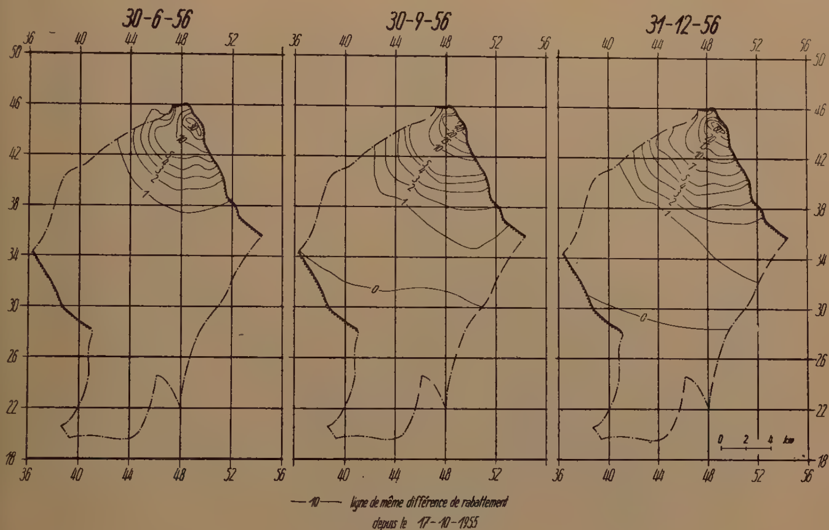


Fig. 4

dans le massif entier ou, au moins, à l'intérieur près du captage soit aussi constante que l'alimentation q de la nappe par l'eau s'infiltrant par les précipitations et la porosité effective P_n du milieu poreux (ce dernier admis sous quelque réserve). Il n'a pas été essayé de déterminer les valeurs exactes tout en connaissant leur variabilité.

En regardant la carte de la surface libre de la nappe on reconnaît que son gradient est tellement petit, excepté dans la proximité immédiate des puits, que l'on peut calculer suivant l'hypothèse de Dupuit-Thiem. En partant de cette idée, la valeur W, dite valeur d'écoulement, fut déterminée pour les lignes équipiézométriques de la surface libre de deux à deux m suivant l'équation

$$W = \int_0^l t \cdot I \cdot d\, l \qquad (1)$$

avec

l = la longueur de la ligne équipiézométrique de la surface libre (prise de fig. 5),
t = l'épaisseur du milieu poreux rempli d'eau (prise des fig. 2 et 5) et
I = le gradient de la nappe phréatique (calculé à l'aide de fig. 5).

Les valeurs W_{79}, W_{77} etc. calculées, correspondant aux lignes équipiézométriques 79, et 77 etc. de la nappe phréatique se trouvent dans le tableau suivant :

TABLEAU 2

ligne équipiézométrique (*m*)	valeur d'écoulement W [m^2]	bassin d'alimentation [km^2]
79	593	154,0
77	789	172,4
75	821	193,4
73	995	210,6
71	1322	223,5
70	1512	228,2
69	1650	232,7
67	1690	237,6
65	1600	244,6
63	1756	250,0
62	1762	252,7

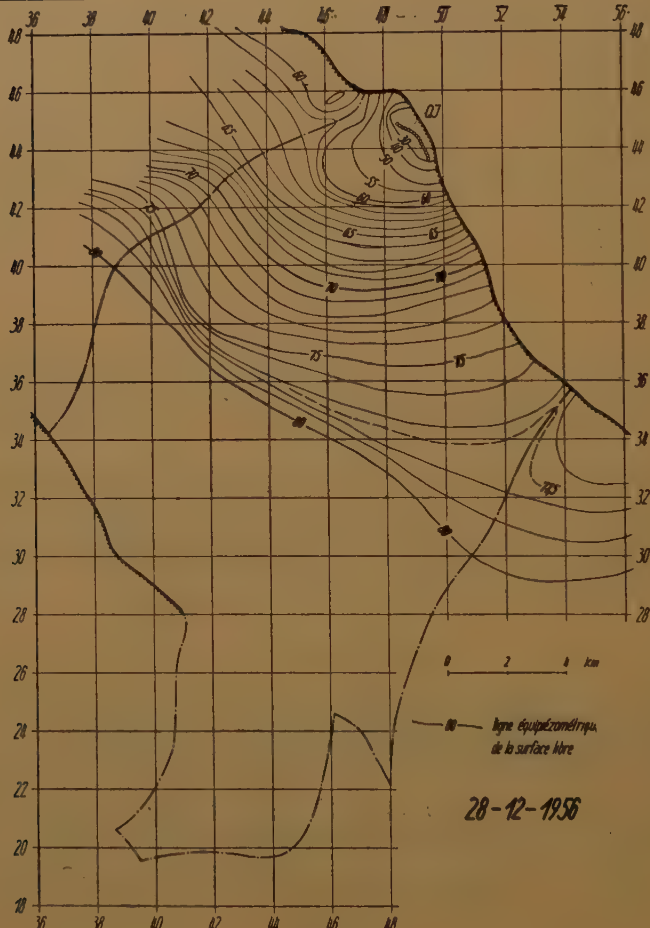


Fig. 5

Elles ont été relevées comme ordonnée sur la surface du bassin d'alimentation se trouvant en amont de la ligne correspondante (voir fig. 6, petits cercles). Les points sont reliés par une ligne moyenne venant de l'origine des coordonnées et se terminant à la surface totale de 268 km² du bassin d'alimentation.

Le débit traversant la section se calcule par

$Q = F \cdot v$ avec

$v = k_f \cdot I$ où k_f signifie la perméabilité

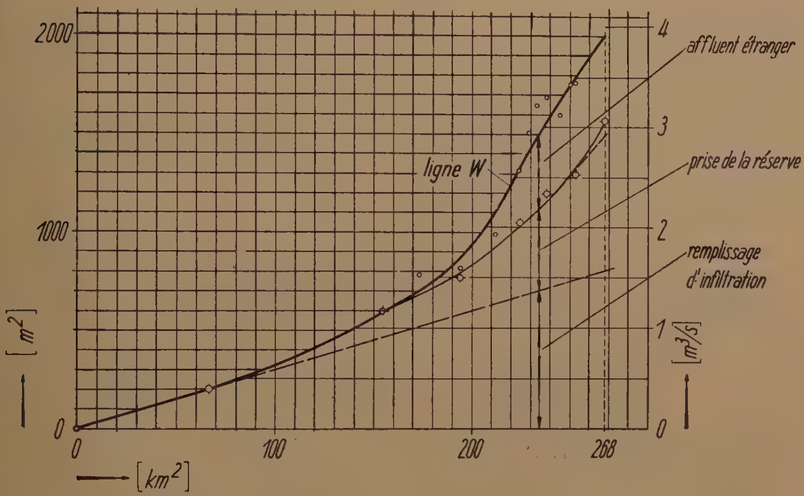


Fig. 6

et F la section verticale le long d'une ligne équipiézométrique de la surface libre jusqu'à la couche imperméable. On obtient

$dQ = k_f \cdot I \cdot t \cdot dl$ et ensuite

(2) $$Q = k_f \int_o^l I \cdot t \cdot dl$$ ou avec (1)

(3) $$Q = k_f \cdot W$$ et

(3a) $$k_f = \frac{Q}{W}$$

L'extrémité de la ligne W correspond au débit total du bassin d'alimentation. Ce débit connu, le calcul de k_f est possible à l'aide de l'équation (3a) pourvu qu'il soit constant. Le débit de 3,9 m³/s, débit des dernières deux semaines et demi avant le 28-12-1956, sert de base à ce calcul. La perméabilité k_f se monte à 0,00195 m/s. Du côté droit de la fig. 6, une deuxième échelle d'ordonnée, échelle de m³/s, a été dressée, de sorte que la ligne W sert en même temps de ligne Q. En s'approchant du captage QI, la quantité d'eau s'écoulant augmente tout en étant zéro au bord du bassin d'alimentation. Fig. 4 montre qu'en dehors d'une certaine ligne il n'y a pas de rabattement de la nappe malgré de prises d'eau. Il faut donc que l'eau s'y écoulant, provienne du remplisasge q de la nappe par l'infiltration des précipitations. Si le remplissage q (m³/s.km²) est constant, il faut que la

ligne W soit rectiligne. Son gradient est proportionné au remplissage q, c'est à dire

$$(4) \qquad q = \frac{k_f \cdot \Delta W}{\Delta F} = \frac{\Delta Q}{\Delta F}$$

On relève de fig. 6 pour F = 50 km² (en partant de l'origine des coordonnées) W = 150 m² et ensuite

$$q = \frac{0{,}00195.\ 150}{50} = 0{,}00585 \ \mathrm{m^3/s \cdot km^2}$$

Il ressort de la fig. 4 qu'il n'y a aucun rabattement dans les 66 km² extérieurs du bassin d'alimentation. Il faut donc, que la ligne W de fig. 6 soit rectiligne jusqu'ici pour dévier ensuite de cette ligne droite (qui correspond à l'alimentation q) et devenir plus escarpée.

Avant de continuer l'analyse de la ligne W, il faut déterminer la vitesse de rabattement de la surface libre. A cet effet, les intervalles suivants du bassin d'alimentation du 28-12-1956 ont été examinés séparément :

TABLEAU 3

désignation de l'intervalle	limitation de l'intervalle
A	du bord extérieur jusqu'au commencement d'un rabattement
B	du commencement d'un rabattement jusqu'à la ligne 79 de la surface phréatique
C	entre ligne 79 et 75
D	» » 75 » 71
E	» » 71 » 67
F	» » 67 » 62
G	au dedans de la ligne 62

Les fig. 4 et 5 servaient de base, et la limite du bassin d'alimentation était celle du 28-12-1956. Les résultats sont réunis dans le tableau 4.

Dans fig. 7, les rabattements des différents intervalles sont dressés et par calcul différentiel graphique, les vitesses de rabattement du 28-12-1956 ont été déterminées.

TABLEAU 4

intervalle	volume du milieu poreux drainé à partir du commencement jusqu'au			rabattement du commencement jusqu'au			surface	
	30-6	30-9	31-12	30-6	30-9	31-12	en détail	en total
		m³.10⁶		[m]	[m]	[m]		[km²]
A	0	0	0	0	0	0	66,3	66,3
B		13,2	26,3		0,15	0,30	87,7	154,0
C	12,9	32,2	41,8	0,33	0,82	1,06	39,4	193,4
D	25,0	41,3	62,0	0,83	1,38	2,06	30,1	223,5
E	23,4	41,6	55,7	1,66	2,95	3,95	14,1	237,6
F	46,0	80,0	91,8	3,05	5,30	6,09	15,1	252,7
G	149,0	226,4	275,2	10,00	15,20	18,45	14,9	267,6

Voici les résultats, comprenant aussi la vitesse d'évacuation de l'eau du milieu poreux en m^3/s :

TABLEAU 5

intervalle	surface en détail [km²]	vitesse de rabattement le 28-12-1956 [mm/s]	vitesse d'évacuation en détail [m³/s]	vitesse d'évacuation en total [m³/s]	prise d'eau de la réserve des pores avec une porosité effective du milieu poreux de $P_n = 13\%$ [m³/s]
A	66,3	0	0	0	0
B	87,7	0,0000232	2,013	2,013	0,262
C	39,4	0,0000185	0,729	2,742	0,357
D	30,1	0,0000966	2,912	5,654	0,735
E	14,1	0,0001116	1,572	7,226	0,940
F	15,1	0,0000480	0,725	7,951	1,035
G	14,9	0,000228	3,396	11,347	1,476

Il a déjà été mentionné plus haut qu'il manque en partie la couche imperméable auprès de la faille de limite du nord-est, de sorte que de l'eau, appelée par la suite « affluent étranger », puisse y parvenir de zones inférieures. Mais ceci n'étant pas encore possible en amont de la ligne 79, il faut que toute l'eau provienne ou du remplissage d'eau q ou de la réserve d'eau de la porosité P_n ou de tout les deux. Le débit de la part du bassin d'alimentation en amont de la ligne 79 se monte à 1,163 m^3/s. La part du remplissage de la nappe s'y monte à 0,901 m^3/s. Il faut que la différence de 0,262 m^3/s provienne des pores. Pour cet intervalle, la vitesse d'évacuation s'élève à 2,013 m^3/s de milieu poreux (voir tableau 5). Les 0,263 m^3/s d'eau venant d'ici, on calcule la porosité effective du sol pour

$$P_n = \frac{0,262}{2,013} = 0,13 \text{ ou } 13\,\%.$$

En admettant que la porosité effective du sol soit constante dans tout le bassin d'alimentation, on arrive à des quantités d'eau prise de la réserve qui se trouvent également inscrites au tableau 5. La valeur maximum se monte à 1,476 m^3/s. Dans fig. 6, ces valeurs aussi sont dressées au dessus de la ligne droite (grands cercles) laquelle correspond à l'alimentation de la nappe q. Les points obtenus ont été reliés par une ligne moyenne. La différence entre cette ligne et la ligne W donne l'affluent étranger. Il se monte au maximum à $Q_{affl} = 0,86$ m^3/s. A cause de raisons discutées plus bas, il est pourtant vraisemblable que l'affluent étranger soit un peu plus grand, de sorte que la part prise de la réserve se diminue et que la courbe en traits interrompus soit valable.

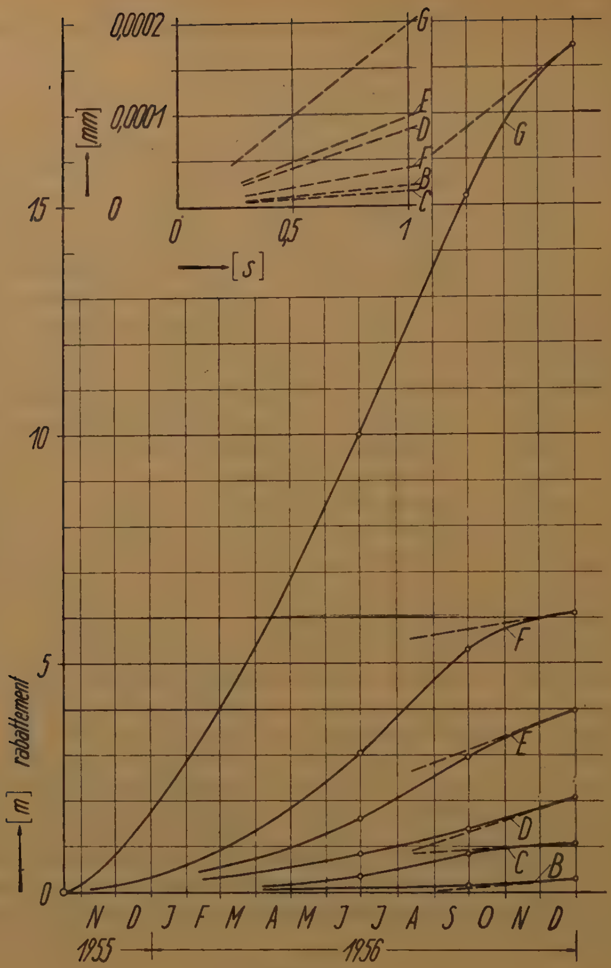


Fig. 7

4) *Le plan de différences valable pour une période de restriction partielle de prises d'eau à partir du 28-10-1956 jusqu'au 8-11-1956 et son examen.*

Pendant certaines périodes, la prise d'eau du captage QI fut fortement restreinte. La dernière restriction importante avant le 28-12 eut lieu du 28-10 au 8-11-1956. Le plan contenant les lignes de mêmes différences de la surface phréatique à la fin de cette période comparé à celle au début se retrouve dans la figure 8. On reconnaît que la surface libre continue à s'abaisser à grande distance du captage QI tandis qu'elle augmente considérablement dans son voisinage. Mais plus au sud-est près de la faille de limite on découvre un second endroit où la surface phréatique augmente. D'après la fig. 2, c'est une région qui n'a pas de couche imperméable. Apparemment de l'eau étrangère provient ici de couches inférieures et entre à travers cette fenêtre géologique ou le long de la faille de limite le milieux poreux au-dessus de la couche

imperméable. Cette eau, refoulée par l'ascension des eaux dans le captage QI, cède vers le haut tout en remplissant les pores autrefois vidés.

Fig. 8

Le volume du milieu poreux vidé de plus se monte à 6,08 . 10^6 m^3 et celui rempli de nouveau se monte à 10,57 . 10^6 m^3. C'est pourquoi il y a 4,49 . 10^6 m^3 plus de rempli que de vidé. Durant l'intervalle susmentionné la prise d'eau du captage QI et des autres se montait à 1,892 . 10^6 m^3. Comme affluent, on ne peut compter qu'avec l'alimentation d'infiltration q, car tout autre est déjà compris dans les volumes de remplissage et de vidange. Le 28-10-1956 le bassin d'alimentation avait une surface de 251 km^2. En admettant que l'alimentation de la nappe soit de $q = 0{,}00585$ m^3/s . km^2, il en résulte un affluent de 1,396 . 10^6 m^3. En outre, le volume de 4,49. 10^6 m^3 du milieu poreux susmentionné est à nouveau rempli d'eau qui s'élève à 0,584 10^6 m^3. Il en résulte un excédent total de prise d'eau de 1,080 . 10^6 m^3. Cette quantité doit être compensée par l'affluent étranger. Celui-ci se monte ainsi à 1,14 m^3/s.

5) *Correction des résultats. Comparaison avec d'autres recherches.*

L'affluent étranger que nous venons de trouver est de 44 % plus grand que celui trouvé au début. C'est probablement dû au fait que la porosité effective P_n du sol rempli à nouveau est moindre que 13 %, sourtout au voisinage des puits du captage QI. A cet endroit, la vitesse de rabattement est la plus grande (voir tableau 5) et par conséquent il est invraisemblable que les pores livrent à l'instant la quantité d'eau totalement possible, circonstance que Ubell a souligné antérieurement ([10]). Conformément il faut calculer avec une porosité moindre pour le remplissage. C'est pourquoi la ligne indiquant la prise d'eau de la réserve (fig. 6) a été corrigée à sa fin (ligne en traits interrompus), la porosité utile étant admise avec 11 %. Il en résulte un affluent étranger d'environ 1,0 m^3/s (voir fig. 6). En même temps, l'affluent étranger, trouvé à l'aide du plan de différences (fig. 8), si diminue également jusqu'à 1,0 m^3/s environ.

Il sera possible de vérifier l'exactitude de la valeur q, si un plus grand nombre de stations d'infiltrations est mis en action. La première a déjà été installée et décrite par Kiel ([3]), qui donne aussi un aperçu des premiers résultats. A l'aide de cette station pour l'année 1956 une valeur probable de $q = 0{,}0062$ $m^3/s . km^2$ a été relevée, qui ne dévie guère de celle de 0,00585 $m^3/s . km^2$. Le rabattement étant en pleine marche, des mesurages ultérieurs rendront possible le contrôle des valeurs trouvées.

La connaissance de q et de P_n ainsi que du volume du milieu poreux rempli d'eau donne la possibilité de déterminer la quantité d'eau utilisable au-dessus de la couche imperméable, ce qui représente la résolution du problème imposé.

D. Résumé.

Etant donné qu'il faut renoncer à l'application de méthodes théoriques pour examiner le rabattement dans un grand bassin, on a eu recours à d'autres procédés. Ceux-ci permettent d'analyser l'origine de l'eau prise du captage à l'aide des résultats des mesurages faits sur les puits d'observation et des mesurages du débit. On détermine d'abord la perméabilité k_f et l'alimentation q de la nappe par l'infiltration à l'aide d'une carte de la surfaec phréatique, et ensuite la prise d'eau de la réserve des pores en utilisant des plans de différences, ce qui révèle la porosité effective P_n du milieu poreux et l'affluent étranger.

L'examen d'un plan de différences entre le commencement et la fin d'une restriction de la prise d'eau permet de corriger les valeurs de l'affluent étranger et de la porosité effective.

Toute l'action du rabattement n'étant que commencée, des mesurages ultérieurs rendront possible un contrôle des résultats.

Le problème imposé : Détermination de la quantité d'eau utilisable du milieu poreux au dessus de la couche imperméable est résolu par les valeurs reçues pour la porosité effective P_n et l'alimentation q de la nappe par l'infiltration.

BIBLIOGRAPHIE

[1] H. Kiel, Grundwasserfragen im Erftgebiet, discours fait à la Baugrundtagung 1956 in Köln.

[2] H. Kiel, Die wasserwirtschaftlichen Probleme im Erftgebiet. Fachheft Wasserversorgung, Wirtschaft und Technik der Kommunalwirtschaft, Düsseldorf, Juli 1956.

[3] H. Kiel, Die Wasserwirtschaft im Erftgebiet in landwirtschaftlicher Sicht. Sonderdruck aus der Vortragsreihe der 10. Hochschultagung der Landwirtschaftlichen Fakultät der Universität Bonn 1956.

[4] N. N. Wasserwirtschaftliche Probleme im Erftgebiet. Ministerium für Ernährung, Landwirtschaft und Forsten des Landes Nordrhein-Westfalen, 1956.
[5] G. Stadermann, Untersuchung über die Auswirkungen der Grundwasserabsenkung im Erftbecken auf den Abfluß in der Erft und Berechnung des «schädlichen» Entzuges. Non publié, 1956.
[6] N. N. Plusieurs travaux, résultats d'observations et de mesurages de la «Staatliche Wasserwirtschaftsstelle Erft beim Wasserwirtschaftsamt Bonn». Non publiés, 1956.
[7] D. Pfeiffer und H. W. Quitzow, Erläuterungen zum Blatt Köln der hydrogeologischen Übersichtskarte 1 : 500 000. Bundesanstalt für Landeskunde, 1955,
[8] H. Weber, Die Reichweite von Grundwasserabsenkungen mittels Rohrbrunnen. Springer, Berlin 1928.
[9] G. Schneebeli, Sur l'hydraulique des puits. Symposia Darcy, Tome II Eaux Souterraines, Publication no. 41 de l'Association Internationale d'Hydrologie, 1956.
[10] K. Ubell, Unsteady flow of groundwater caused by well-drawdown. Symposia Darcy, Tome II Eaux souterraines, Publication no. 41 de l'Association Internationale d'Hydrologie, 1956.

DEVELOPMENT OF THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS (*)

JOHN G. FERRIS AND A. NELSON SAYRE **

ABSTRACT

In reviewing progress to date, we find that, since the beginnings of quantitative ground-water hydrology in Europe a century ago, interest in the development of quantitative tools in this subject has spread over the world to enlist workers from many fields of science. Much of the development of methods, tools, and skills for quantitative appraisal of ground-water sources has occurred within the past few decades and now, because of the great strides made in this period, hydrologists can determine the ground-water potential of an area with the same degree of accuracy obtainable in the appraisal of surface water.

With Darcy's development of the law governing fluid permeation through sands and with Dupuit's application of that law to the problem of radial flow toward a pumped well, the development of water supplies from wells was placed on a rational basis. Others added analytic expressions for the flow of water from streams to wells or galleries and for the effects of drains and canals upon the ground-water regimen. As field experience increased, confidence was gained in the applicability of quantitative methods and interest was stimulated in the development o fsolutions for more complex hydrologic problems.

An important milestone was Theis' development in 1935 of a solution for the nonsteady flow of ground water, which enabled hydrologists to forecast the yield of wells and to appraise their influence in both time and space.

Ground-water hydrology, as an offshoot of geology, was dominated initially by the explanatory-descriptive method which was then in favor in the parent science. At the time, water needs were rather small and the principal objective was to determine where the water was rather than how much was available. Thus, the new science was directed primarily to the study of the origin and occurrence of ground water, with particular reference to identification and description of the principal water-bearing rocks.

The Industrial Revolution, with the development of the steam engine, freed man of his dependence upon gravity to move water, but greatly increased his water demands. For a time, industrialization was confined to the flood plains of principal streams because of the limitations of pumping equipment. As surface waters became fully appropriated and contamination further complicated their utilization, attention was directed to the utilization of ground-water sources and to the problems associated with their development. Before long, improvement sin well-construction methods and advances in the design of pumps opened new horizons, not only geologically but also economically. The large-scale development of wells capable of supplying the water needs of agriculture, industry, and public supply permitted the development of water supplies from areas other than the flood plains, where the development of water had been limited to a source subject to extreme variations in quantity and quality.

Continued rapid expansion of the industrial economy and increasing urbanization resulted in ever-increasing water demands. The yields of wells were increased

(*) Publication authorized by the Director of the U. S. Geological Survey.
(**) Research Engineer and Chief, respectively, Ground Water Branch, Water Resources Division, U. S. Geological Survey.

and this, in turn, involved greater drawdowns. As urban areas expanded, the increasing competition for the same water source resulted in marked lowering of ground-water levels in areas of intensive development. Consequently, the nature and urgency of water problems shifted from merely locating wells to determining how much water could be withdrawn and how that amount of water could be developed most economically. Ground-water hydrologists turned their attention to the new problem and gradually evolved a quantitative methodology to evaluate the influences of intensive development.

As described by the authors (1956), early developments in quantitative methodology were limited to the analysis of steady-state flow toward wells, and their applicability to field problems was most restricted by qualifying conditions. However, these important beginnings formed the framework for all that followed. The real breakthrough came with the development by Theis in 1935 of the nonequilibrium formula and his exposition of the analogy between the conduction of heat in solids and the flow of water through porous media. There followed many useful corollary equations and other analytic formulations for solving problems of ground-water flow toward wells, drains, or galleries. Mathematical models were developed for the flow of ground water toward intake structures in buried channels, reentrants, horst and graben structures, and even boxlike aquifers found in some areas of complex faulting. Extensions were made to evaluate the influence of infiltration from the surface, from lakes and streams, and from leakage through confining beds.

Meanwhile, development of the resource so intensified that, in some areas, the problem changed from the determination of how much ground water could be withdrawn to how long such a rate of withdrawal could be maintained before exhaustion of the supply. With the success of analytic formulations demonstrated, this was the approach to problems of regional evaluation of the water resource. In some instances the results were rewarding, but more often the complexity of geohydrologic regimens ruled out the use of analytic methods because the idealized setting of mathematical models did not satisfy the geologic variable. The ground-water hydrologist then turned to nonanalytic methods of finite-difference equations and to the use of hydraulic, elastic, and electrical analogs.

Encouraged by success in adapting analogs and finite-difference methods to some flow systems, investigators attempted the solution of more complex systems. However, it immediately became apparent that definition of the geologic variable must be refined greatly in order to set up appropriate models or analogs for study of complex flow systems. Further, it became evident that for most research and fact-finding agencies, the task of defining the geologic variable in sufficient detail for model or analog construction would become a major consideration in evaluating some regional problems of water-resource development. Thus, until the complexity of the problem and the difficulties of analysis are better appreciated, budget availability for water-resource investigations largely limits regional application of quantitative methodology.

Developments to date in the evaluation of regional flow systems emphasize the need for more detailed study of the geology as it affects the occurrence and movement of groundwater and the effect of geologic controls before quantitative methodology can be extended to handle the wide range of the geologic variable.

REFERENCE

FERRIS, J. G., and SAYRE, A. N., 1956, The quantitative approach to ground-water investigations: Econ. Geology, Fiftieth Anniversary Volume. 1955.

THE PRINCIPLES OF REGIONAL ESTIMATION OF UNDERGROUND WATER NATURAL RESOURCES AND THE WATER BALANCE PROBLEM

Dr KUDELIN B.I.
The Moskow State University

ABSTRACT

1. Resources of underground waters are meant as a part of underground water reserves renewed in the process of a general cycle of water.

2. The methods used in hydrogeology to determine underground water resource requires some prospecting and experimental work which is sometimes difficult in practice for small territories.

3. To make a regional evaluation of natural resources in ground waters the river hydrograph was divided by the genetic types of nourishment. The section of the hydrograph of the general river run-off formed due to the ground run-off represents natural resources of the ground waters of the river basin. This approach is different from those used before and yields satisfactory results.

4. To make a regional estimate of natural resources of artesian waters the author put forward a method of studying the average perennial water balance of nourishment or discharge of artesian basins by using the following equation:

$$x_0 = y_0 + z_0 \pm w_0, \quad (1)$$

which is solved regarding

$$\pm w_0 = x_0 - y_0 - z_0, \quad (2)$$

where $\pm w_0$ is the deficiency of excess or moisture in regions of nourishment or discharge of the artesian basin respectively; x_0, y_0 and z_0 are average perennial values of precipitations, river run-off and evaporation.

Moisture deficiency in the nourishment region ($+ w_0$) indicates a perennial value of the artesian basin, the moisture excess in the discharge region ($- w_0$) indicates the value of the artesian run-off, i.e. $\pm w_0$ characterizes the average perennial value of natural resources of underground waters of the artesian basin.

5. The methods mentioned above give a regional estimate of natural resources of ground and artesian waters but do not exclude and cannot substitute detailed hydrogeological prospecting and experimental operations when the problem of water supply of concrete locations are touched.

6. The experience in applying the above methods for vast territories yields satisfactory results. Maps of the ground and artesian run-off can be compiled for vast areas of the globe.

7. The average perennial water balance of land is until now studied by the equation:

$$x_0 = y_0 + z_0, \quad (3)$$

which does not take into account a deep underground run-off.

This is not always correct. As investigations showed the value of the artesian run-off in some basins can be compared to that of the ground run-off and therefore the deep run-off must be a due term of the water balance equation. Evaporation rates should be computed with allowance to the deep run-off:

$$z_0 = x_0 - y_0 \pm w_0. \quad (4)$$

Evaporation maps, in some countries compiled on the basis of the equation (3), are to be revised and made more accurate.

8. Maps of a perennial water balance must be compiled with allowance to geostructural and hydrogeological peculiarities of river basins and contain, in the whole, not three (as on modern maps) but four isolines systems: isolines of precipitation rates (x_0), run-off rates (y_0), evaporation rates (z_0) and infiltration rate for deep-water aquifers ($+ w_0$), or rates of the artesian run-off (nourishment) in a river basin ($- w_0$).

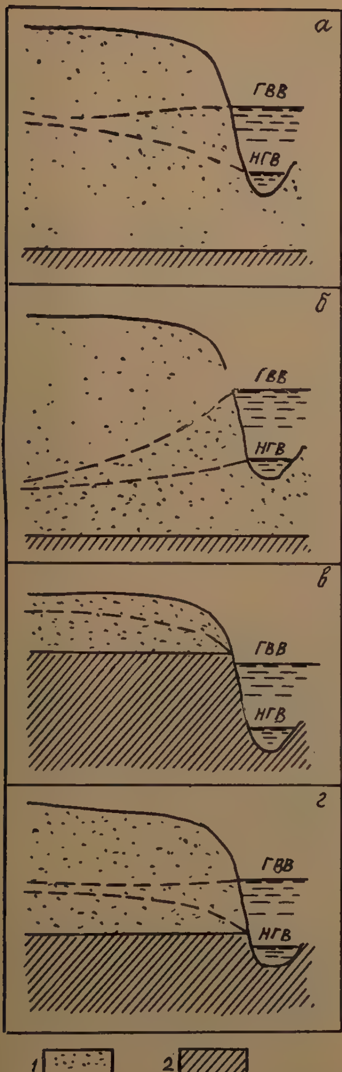


Fig. 1

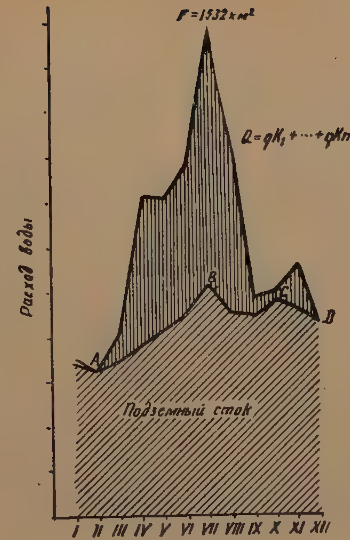


Fig. 4

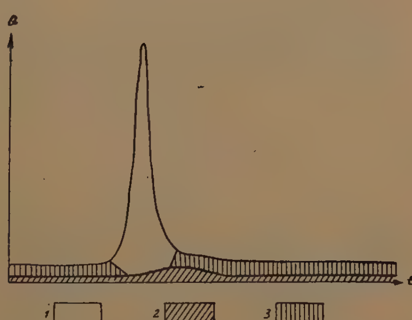


Fig. 6

Fig. 1 — Ground waters hydraulic connection with the river scheme (after Veviorovsky M. A.)

a) full hydraulic connection of water-bearing horizon with the river;
b) water-bearing horizon having full hydraulic connection with the river under arid climatic conditions with deep lying level of ground waters;
c) absence of hydraulic connection of water-bearing horizon with the river;
d) water-bearing horizon having full periodic hydraulic connection with the river.

Conventional Notations:

1 — permeable rocks; 2 — water-resisting rocks; dotted line — ground waters level; L. W. H. river water low horizon; H. W. H. high river water horizon.

Fig. 4 — The underground discharge separation according to the river Malka hydrogram — 1940 (by Makarenko's method).

Fig. 6 — The underground discharge separation scheme — with mixed ground supply.

Conventional Notations:

1 — surface discharge; 2 — ground discharge of water-bearing horizons having no hydraulic connection with the river; 3 — ground discharge of water bearing horizons hydraulically connected with the river.

I. General.

1. By the term of underground water natural resources is meant the part of underground water resources which is annually renewed in the process of general moisture circulation.

2. One of the main problems of modern hydrology is the mapping of underground and artesian water natural resources for large areas.

3. The method of determination of underground water resources known in hydrological practice requires the carrying out of detailed prospecting and experimental work which is difficult to achieve for large areas on economic grounds.

4. According to genetic sources of supply the idea of a river hydrogram division has been used for regional estimation of ground water resources. The part of the general river discharge hydrogram which is formed from ground discharge into the river represents ground water natural resources.

The author has worked out the method of river hydrogram division taking into consideration the river basin hydrological structure, the regime of underground discharge into the river from all water-bearing horizons drained by the river and also spatial regularity of discharge regime. The above approach to the solution of this problem differs radically from the others employed previously and gives more satisfactory results.

II. The Method of Ground Discharge Estimation.

5. The underground supply of rivers consists of ground and artesian discharge into the river. The dynamics of the underground discharge from different water-bearing horizons drained by the river system depends on the degree of hydraulic relation between water-bearing horizons and the river. In accordance with the study of the river supply it is necessary to distinguish:

1) water-bearing horizons having full hydraulic connection with the river*.
2) Water-bearing horizons not conncected hydraulically with the river.
3) Water-bearing horizons periodically connected with the river. (fig. 1).

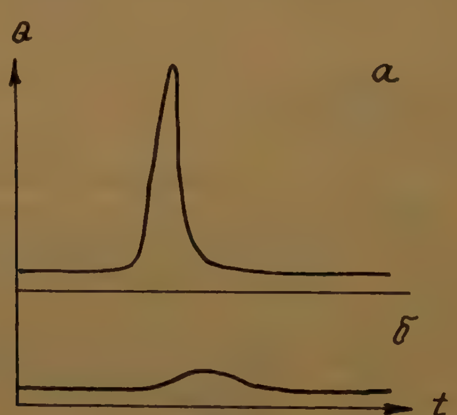


Fig. 2

(*) Case «B» is not discussed here.

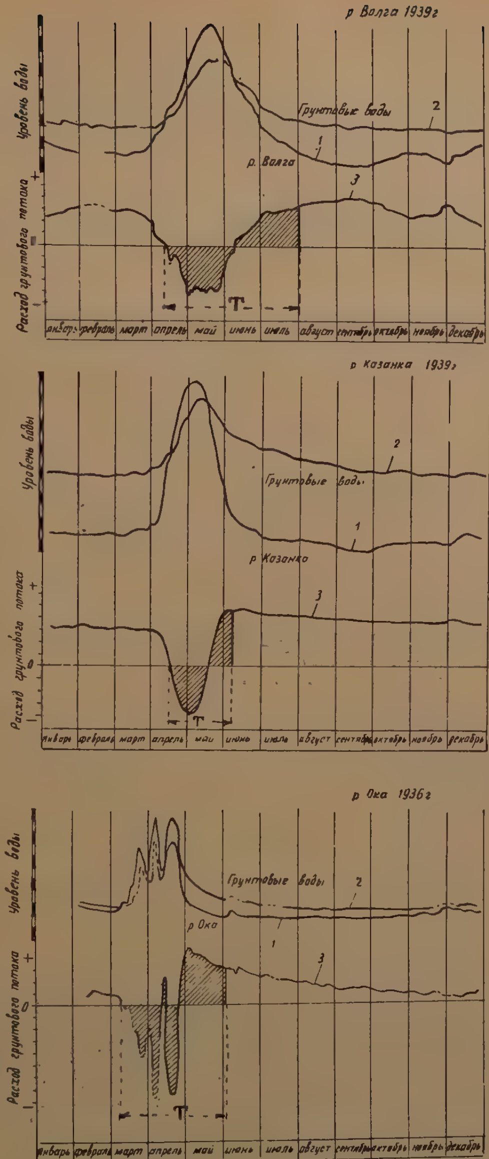


Fig. 3 — Consistent curve diagrams of the level fluctuations

a) the Volga (1) ground waters of river-front zone (2) single water discharge of ground flow (3) — 1939. The water-bearing horizon 150-170 m. thick is confined to the Permian and Carboniferous fissured limestones and dolomites having good hydraulic connection with the river (water — collecting area F = 1264000 km².)

b) the Oka (1) ground waters of river-front zone (2) single water discharge of ground flow (3) — 1936. The water-bearing horizon 12-14 m. thick is developed in alluvial deposits, fissured limestones and in marls of the Upine layers. It has a good hydraulic connection with the river. (F = 59.400 km².)

c) The Kazanka (1), underground waters in water-front zone (2) single water discharge of underground flow (3) — 1939. The water-bearing horizon 50 m. thick is in the sand and loamy alluvial deposits and also in sandstones, limestones and delomites of the Kazan layer. It has a good hydraulic connection with the river (F = 2660 km².)

T — is a period of surface outlow riverside control.

Water-bearing horizons of ground water without hydraulic connection with the river have discharge regime and phases very similar to those of the run-off. The difference is that the peak of the ground-water discharge is not so distinct as that of the river and that it comes later than that of the flood-water (fig. 2).

In comparison with surface waters water-bearing horizons hydraulically connected with the river have different regime and the opposite direction of discharge phases. The run-off maximum corresponds to the underground discharge of this category (fig. 3).

The discharge regime of water-bearing horizons having periodical hydraulic connection with the river is mixed: when the river horizons are low their regime corresponds to the first category of water-bearing horizons, when high — to the second one.

In their turn ascending springs fed by the water from deep-seated artesian water-bearing horizons and emerging higher than the river cut-off do not show flow fluctuation characteristic for the above mentioned underground discharge categories. Hence it follows that the hydrogram form of the underground discharge will depend on the proportion of the above kinds of supply.

6. In practice the river hydrogram division is made on the grounds of hydrogeological conditions of the river basin.

Case 1. The river subsurface supply is mainly made by ground waters not connected hydraulically with the river (fig. 1 «b») (Seems to be characteristic for mountain rivers).

The river hydrogram division is made according to the method worked out by Makarenko F.A.

The formula of underground discharge estimation is as follows:

$$Q = qk_1 + \quad . \quad . \quad . \quad . \quad . \quad + qk_n, \qquad (1)$$

where q is the low river discharge (taken in this period as the measure of river supply by ground waters);

$k_1 \ldots k_n$ are coefficients (monthly, for instance), which are characteristic of the annual regime of ground discharge (ouflow) into the river and inferred from the curve of the regime of the summary flow of total discharge of the basin main springs where coefficient k corresponding to the regime of low water discharge into the river is 1.0 (fig. 4*).

Case 2. The underground river supply is mainly maintained by ground waters hydraulically connected with the river. (fig. 1 «a») (characteristic for lowland rivers) The estimation method rests on the following grounds.

The regime of subsurface discharge from ground-waters hydraulically associated with the river is closely connected with the surface water-passage itself. When the water level rises there occurs the lessening of hydraulic gradients as well as of water discharge into the river (the head water phenomenon.) In the river-side zone when the spring flood stage is rising there are formed opposite hydraulic gradients of ground flow and river water infiltration into the banks. In the flood — abatement soon after its peak was passed and when a river water level falls very quickly, the ground flow table becomes again inclined to the river and there begins the reverse discharge of the infiltering river water into the banks. The river water infiltration into the banks in the time of rising flood stage and its reverse motion when the abatement begins is called a bank regulation of the surface discharge. As it has been shown by the experience (fig. 3) the general duration of the surface discharge bank control is approximately equal to the general period of spring flood. The mathematical

(*) Makarenko F. A. — On River Underground Supply.
Dokuadhi Akademiu Hayk CCCP, vol. LVII, N 5, 1947.

expression of this bank control may be expressed by such an approximate algebraic equality which holds good for every river alignment:

$$-A + A' - 0. \quad \ldots \ldots \ldots \quad (2)$$

where A is a river water infiltration value per unit of the bank river length at the time of the rising flood stage (negative underground feeding); A′ — is a value of ground water discharge into the river per unit of a river bank length when the flood is abating.

With regard to the river alignment, this equation (2) is at the same time an equation of the river ground supply by waterbearing horizons hydraulically associated with the river in the period of high water. Hence it follows that for every river alignment the ground supply from water-bearing horizons, hydraulically connected with the river may be taken as zero when estimating the water-balance at the time of high flood.

To estimate the underground outflow in the locked river alignment (i.e. along the river basin) from water-bearing horizons which are hydraulically connected with the river it is necessary to take into account the basin size and spatial regularity of underground discharge development. When the basin is large enough and there exist definite conditions of high-flood development ground waters drained in the upper parts of the basin can pass through the locked river alignment while in the measuring station alignment the ground discharge is absent. It is easy to estimate if there are the data about the flood beginning and its end at the head of the basin and also those of the running water velocity.

Let us take for example the river Bolshoi Cheremshan basin where one main ground water horizon is developed and which has a very good hydraulic connection with the river.

The Bolshoi Cheremshan catchmet basin in the Melekess alignment is F = 11780 sq. km. The 1940 hydrogram is given in fig. 5. The low water underground discharge

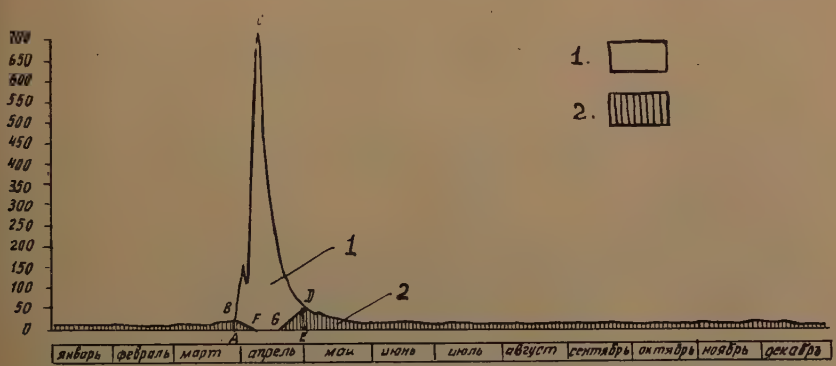


Fig. 5 — The Bolshoi Cheremshan hydrogram near Melekes (town) — 1940.
Conventional Notations:
1 — surface discharge; 2 — ground discharge.

is separated from high water by straight verticals A.B. and D.E. On March 30 the high flood began simultaneously all over the basin. From this moment the underground supply was stopped but ground waters which had come into the river before March 30 would flow down the river together with the flood wave. The running rate estimated from the flood peak passage is 34 km. per day*. The distance from head waters

(*) If flow rates measured with hydrometric propeller are available it is better to make use of them.

to the Melekess alignment is 313 km. Hence, ground waters will flow down for 9 days and those from the farthermost parts of the basin will pass the locking alignment on April 8 (F fig. 5). The lowering discharge of ground waters passing by Melekess will take place along the straight line BF.

In the Melekess alignment the high flood ended on April 29 and in the head waters on April 11. From April 11 there began ground water inflow into the river head waters at the expence of the basin ground water main storage. In accordance with the above stated they will reach calculated alignment in 9 days, i.e. on April 20 (point G. fig. 5) or 9 days earlier than the beginning of underground supply in the basin lower reaches. The incraease of the underground outflow will take place along the line GD (fig. 5). By April 29 the riverfront control of the surface discharge as well as the melt-water discharge will have been finished along the whole basin and by this time the river will be fully fed by underground waters. In 1940 high-floods were absent and the rest of the hydrogram is connected with underground discharge (fig. 5).

Case 3. The river ground supply is mixed:

a) by ground waters hydraulically connected and b) disconnected with the river (fig. 1 «a», «b»).

The river hydrogram separation scheme is shown in fig. 6. The estimation method for every kind of ground water discharge is clear from the above.

Case 4. (The most common). The river is fed by two above mentioned kinds of ground water and by artesian waters as well. For the sake of simplicity let us suppose that the artesian discharge is maintained by ascending springs fed by head water-bearing horizon not connected hydraulically with the river and has no visible annual flow fluctuations. Then according to the genetic kinds of supply, the river hydrogram separation will be as follows (fig. 7).

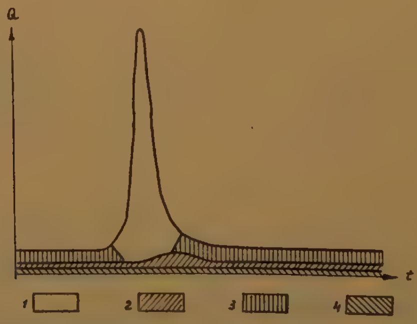


Fig. 7 — Underground discharge separation scheme according to the river hydrogram with mixed ground and artesian supply.

Conventional Notations:

1 — surface discharge; 2 — ground discharge of water-bearing horizons having no hydraulic connection with the river; 3 — ground discharge of water-bearing horizons hydraulically connected with the river; 4 — artesian discharge of ascending springs fed by artesian water-bearing horizon having no hydraulic connection with the river.

The proportion-ratio of different water-bearing horizons in the river supply is determined as a result of hydrogeological survey.

III. The Method of Regional Estimation of Artesian Water Natural Resources

7. The pumping out method of artesian water natural resources determination which has been worked out in hydrology cannot be used for estimation of general underground water resources of large artesian basins on account of high cost of boring and experimental work.

8. For regional determination of artesian water natural resources the author suggests a method of studying the mean pernennial water balance for supply and discharge areas of artesian basins using the following equation :

$$X_0 = Y_0 + Z_0 \pm W_0 \quad \ldots \ldots \ldots \quad (3)$$

which is solved relative to $\pm Wo$:

$$\pm W_0 = X_0 - Y_0 - Z_0, \quad \ldots \ldots \ldots \quad (4).$$

where $\pm W_0$ is shortage or surplus of moisture in the areas of artesian basin supply or discharge respectively: X_0, Y_0 and Z_0 are the average perennial precipitation values for the river discharge and evaporation.

The moisture shortage in the supply area ($\pm W_0$) shows the average perennial value of artesian basin supply, the moisture surplus in the discharge area ($- W_0$) is the artesian discharge value, that is, $\pm W_0$ characterizes the average perennial value of artesian basin underground water natural resources.

If the river basin or its part be taken as an elementary water balance area then the problem of determining artesian basin natural resources will be reduced to the study and making up of the average perennial water balance of closed rivers basins, i.e. geophysical problem.

IV. An Attempt of Regional Estimation of Ground and Artesian Waters Natural Resources.

9. The Dnieper—Donetz depression in whose Paleozoic, Mezozoic and Paleogene mighty thickness of sedimentary rocks are developed abundant artesian-waters with clear fresh water which occur in Jurassic, Senoman-Albian and Buchaksko-Kanevian deposits. It was chosen as an object for regional estimation of underground water natural resources. The ground waters circulate in rocks of different age beginning from the Upper Devon (at the north-western limb of the depression serving as an artesian basin supply area) to the Recent Quaternary deposits.

The above mentioned territory occupies the left side of the Dnieper basin and the upper part of the North Donetz with the total area of about 300,000 km². The well developed net of meteorological stations and hydrometrical parts having at their disposal perennial discharge observations and also satisfactory geological and hydrogeological knowledge made available all the material necessary for the estimation of ground and artesian water general resources by the above mentioned method which does not require the detailed exploration and experimental work.

A. *Ground Water Natural Resources.*

10. The ground discharge has been estimated for 3 hundred years observations according to 30 river alignments regulary located all over the territory. As a result there have been drawn maps characterizing ground discharge distribution over the territory (figs. 8-12). All these maps reflect average data for the period of observations. The ground discharge characteristics for different years are given in tables.

Fig. 8 — Map of the mean annual underground discharge into the river (layer in mm.)
Conventional Notations:
The underground discharge layer — mm. per year: 1) more than 80, 2) 80-70 3) 70-60, 4) 60-50, 5) 50-40, 6) 40-30, 7) 30-20, 8) 20-10, 9) less than 10.

The water-bearing horizons drainage map as well as the river underground supply summary hydrogeological column have been made. For the estimation of separate water-bearing horizons resources such a map was given as an example for one of the regions (fig. 14).

For the greater part of the territory it became possible to get ground discharge perennial series. At the same time it became clear that the ground discharge has pronounced annual and seasonal fluctuations and well marked zoning (figs. 8-12). The 29 year observations have shown that the Propoisk alignments average annual value of the ground discharge in the river Soge basin (F = 17660 km^2) fluctuated from 47.0 mm. (1901) to 106.6 mm. (1928), i.e. 2.3 times as great and the discharge coefficient from 7.8 % (1901) to 18.5 % (1919). Approximately the same ground discharge perennial fluctuations are noticed in the Desna and the Seim basins. Still more significant ground discharge fluctuation amplitude is in the basin in the southern river basins where, for instance, in the river Psel basin to the Zapselje alignment (F = 22420 km^2) the 13 years ground discharge fluctuated from 5.0 mm. (1939) to 50.4 mm. (1933), that is more than 10 times as great at the mean value of 26.5 mm. and the discharge coefficient from 1.3 % (1939) to 7.7% (1933) at the mean value of 5.4% etc.

The pronounced annual and seasonal ground discharge fluctuations rise a question of necessity of getting perennial characteristics for the estimation of ground water natural resources, that, as a rule, cannot be achieved by usual hydrogeologic methods.

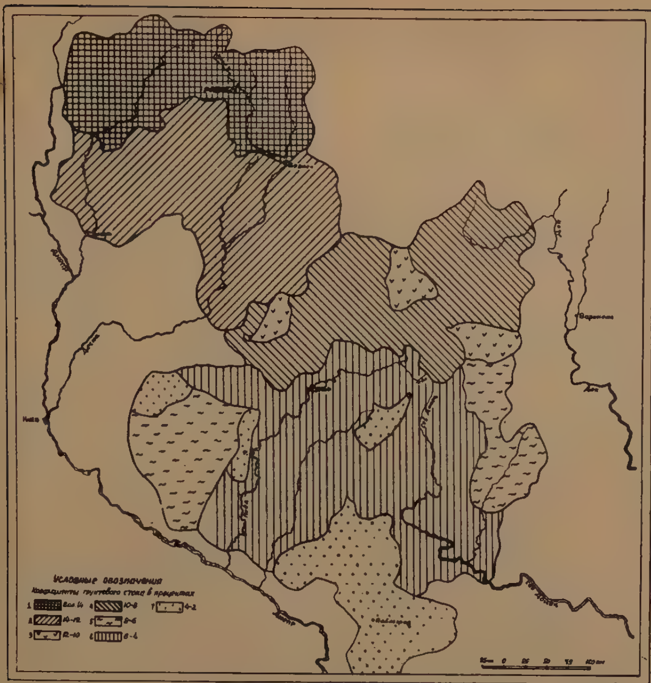


Fig. 9 — Map of the mean annual coefficients of underground discharge.
Conventional Notations:
Underground discharge coefficients in per cents: 1) more than 14, 2) 14-12, 3) 12-10, 4) 10-8, 5) 8-6, 6) 6-4, 7) 4-2.

Fig. 10 — Map of isolines of underground discharge mean annual modules (litre per second km²).

Fig. 11 — Map of isolines of underground discharge mean annual coefficients (in per cents).

Fig. 12 — Map of isolines of underground discharge mean minimum modules (litre per second km²).

Fig. 13 — Hydrogeological map of river underground supply (water-bearing horizons drainage).

Conventional Notations:

Regions of drainage waters developed in deposits:
I. Devonian, Yurassic, Lower Cretaceous, and Senoman;
II. Lower Cretaceous and Upper Cretaceous;
III. Upper Cretaceous;
IV. Upper Cretaceous and Tertiary;
V. Tertiary.

The ground discharge values found by the hydrogram separation characterize average values of ground discharge of the whole river catchment area (to the measuring station alignment). They are fairly accurate as the regional characteristic of ground water natural resources. No other existing methods can give more accurate ground discharge area characteristics (for large areas) than that obtained by the above methods. At the same time the hydrogram separation method does not exclude and cannot replace the detailed hydrogeological investigations while solving water-supply questions of some concrete objects.

The ground water natural resources maps made by this method will make up for the existing limitation which still exists in the study of ground waters when such

№№ п/п	Гидрогеологическая колонка	Возраст	Литология	Название и тип водоносного горизонта	Степень гидравлической связи с рекой	% участия в подземном питании рек
1		$Q_{III}^{eol\text{-}d}$	Суглинки	Слабое водопроявление типа верховодки	—	—
2		N^{pet}	Песок, м/з.	Полтавско-харьковский, безнапорный	Гидравлически не связан	0,66
3		P_g^{ch}	Глинистые пески			
4			Глины	Водоупор	—	—
5		Cr_2^{sn}	Мел, мергель	Мергельно-меловой, безнапорный или с местным напором	Гидравлически связан	99,34
6			Нетрещиноватый глинистый мел	Водоупор	—	—

Fig. 14 — Summary hydrogeological column of river underground supply.

an all important characteristics as ground water amount does not attract proper attention. Together with the maps of depths of occurrence of ground waters and its chemical composition they will render the study of our country's water resources more complete and thorough.

The time has come when *ground water natural resources maps must become an integral part of all the documents which a hydrologist presents as a result of hydrogeological survey.* Such maps will find extensive application in hydrology as well.

B. *Artesian Water Natural Resources.*

11. For the estimation of artesian water resources by the formula (4/ the mapped area of supply of the Dnieper-Donetz artesian basin has been divided into eleven main water balance sections inside which there were separated out 26 smaller sections confined to the individual water basins (fig. 15). The equation (4) members X_0 and Y_0 were found in reference books according to data on climates and hydrology, Z_0 was estimated by geophysical methods which afterwards (concerning certain points) were correlated with the experimentally observed values of the total evaporation at the agrometeorological stations.

The water balance estimations have shown a very interesting picture. They made to a great extent possible to define and detail hydrogeological characteristic of

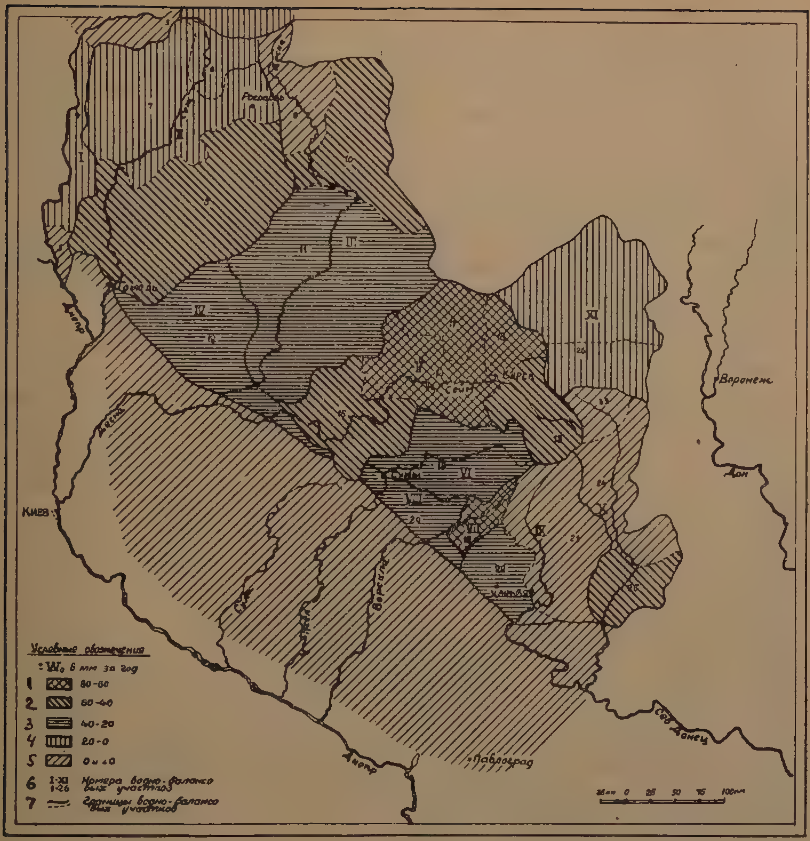


Fig. 15 — Map of mean perennial values $\pm W_0$ for the Dnieper-Donetz artesian basin territory (mm per layer).

Conventional Notations:

$\pm W_0$ annual mm 1.80-60, 2.60-40, 3.40-20, 4.20-0, 5.0 and less than 0, 6. water balance sections numbers 7. water balance sections boundaries.

the supply area of the Dnieper-Donetz artesian basin. At the north-eastern extremity of the Donetz basin proper (Smolensk—Orsha section— F = 3930 km²) and the upper reaches of the river Oskol (to Evdotzkaya F = 1540 km²) serve as the local discharge areas of head waters. Here the annual water-balance negative increment is 59.2 and 46.0 mm respectively, i.e. 10.2% and 8.6% from the perennial average precipitation value. The water-balance negative increment (of less value) has been received from the other sections with the total area of 56.340 km². Simultaneously these water-balance estimations showed places of the most intensive absorption of atmospheric waters. In the Seim basin which is generally noted for its high infiltration the sections occupied by the tributaries Svap and Tuskar as well as the Seim valley section between Ljebuyagie and Rilsk are the places of the most extensive supply by the water-bearing horizons. It is quite natural because within the mentioned basins is noted the greatest exposure of Senoman and Lower Cretaceous sands.

Here the average perennial value of deep infiltration ($+ W_0$) amounts to 69-76 mm a year, which exceeds the surface discharge into the river and makes up more than 12 — 13% of the basin precipitation. The water-balance estimations showed that out of 216350 km² occupying the north-eastern flank of the Dnieper-Donetz depression (referred by some authors to the supply area), 104100 km² do not play any significant part in the artesian basin supply, and that over the area of 5470 km² there occurs very intensive discharge of head waters. The hydrogeological analysis of water-balance estimations has shown that their results correspond to the geostructural and hydrogeological conditions of different water-balance sections. So, here is the case when for the first time in hydrogeological practice, the artesian basin supply and discharge areas of the artesian basins are separated not only on geological evidence but also on the unbiased data of waterbalance estimations establishing the places of precipitation absorption and the places of surficial outflow of artesian head waters. Both the supply and the discharge areas themselves are quantitatively characterized by the infiltration or artesian discharge values.

The water-balance estimations show that the average perennial moisture deficiency in the Dnieper-Donetz artesian basin supply area is approximately $5.10^9 m^3$ a year. This amount of infiltration water forms a deep underground discharge in the Paleozoic, Mezozoic and Paleogene thickness of the Dnieper-Donetz depression which has three main directions: S.W,S. and S.E. Among the mentioned directions the artesian discharge power is approximately distributed in the following manner.

a) the N.W. branch directed towards the upper Dnieper Valley (above Kiev) is $1.6.10^9$ m³ a year,

b) the central southern branch has its discharge area of $2.4.10^9$ m³ a year in the Middle Dnieper valley (somewhat above Kiev-Dnepropetrovsk); and

c) the S.E. branch directed towards the Donetz basin is 1.10^9 m³ a year. The artesian basin supply center is the river Seim in whose basin the main masses of artesian discharge originate; the vast amount of precipitation comes to the artesian basin from the Desna and the Soge basins. At the given value of deep infiltration the general discharge of artesian waters securred by atmospheric supply will on the average be for 1 km of frontal flow (according to isopiestic line of 110 m. abs.) a day:

1) for the whole artesian basin 16200 m³,

2) for the N.W. part of the basin 15.400 m³, ³) for the central part 18.600 m³ ⁴) and for the eastern one 13.400 m³. In determining the artesian waters discharge in the area of supply the average discharge for 1 km flow front will decrease and will give — 13100 m³ per day for the N.W. part of the artesian basin and 12500 m³ for the eastern part; the central part discharge remaining changeless.

The hydrogeological conditions of the Dnieper-Donetz artesian basin, the hydraulic association of different water-bearing horizons and the similarity of their supply areas do not allow to give the exact difinition of different water-bearing horizons. Using the geological section it is possible to distribute the general discharge of artesian waters of sedimentary beds in proportion to the thicknesses of water-permeable series taking into account the changes of underground water circulation conditions with the depth. This gives approximate values of underground water discharge according to different water-bearing complexes.

The comparison of water-bearing horizons capacity computed by the water-balance method with artesian water exploitation data showed a satisfactory coincidence of results. Thus the water-balance method may be applied as a method for regional estimation of artesian water natural resources.

12. The land average perennial water balance is still studied according to the equation (5):

$$X_0 = Y_0 + Z_0, \quad \ldots \ldots \ldots \ldots \quad (5)$$

without taking into account the deep underground discharge.

Investigations together with the above mentioned Dnieper-Donetz artesian basin investigations show that for some basins the artesian discharge value (table 1) is correlated with the ground discharge and so the depth discharge ($\pm$ W_0) must be an equal member of the water balance equation (eq. 3).

Correspondingly the evaporation rate should be computed with regard to the depth discharge (6):

$$Z_0 = X_0 - Y_0 \pm W_0 \quad \ldots \ldots \ldots \ldots \quad (6)$$

The evaporation maps made in some coutries on the basis of this equation solution (6) concerning *Zo* are:

$$Z_0 = X_0 - Y_0 \quad \ldots \ldots \ldots \ldots \quad (7).$$

13. The complete average perennial water balance of the Dnieper-Donetz Artesian basin supply area is given in table 1.

The balance given in this table contains all important elements of the land water balance necessary for practical estimations.

It shows the division of precipitations in this basin into the discharge and evaporation an attempt being made here for the first time to divide the discharge into surface, ground and artesian discharges. In this it differs on principle from the previously made water balances.

The introduction of the water balance new member, namely the underground depth discharge contributes to the exactitude of all other members of the water balance.

When considering the table 1 we shall see that in the Seim, the Psel, and the Vorskla basins the artesian discharge exceeds the ground discharge and in the other two main left-side tributaries of the Dnieper, the Soge and the Desna it is a very important value worth considering when estimating water balance.

Hence the idea of universalism of the average perennial water-balance equation —$X_0 = Y_0 + Z_0$ introduced at the end of the last century should be considered as out-of-date and estimation based on this equation are rather rough and do not correspond to the geostructural and hydrogeological conditions of river basins.

If the average perennial water-balance of supply area of the Dnieper-Donetz artesian basin were computed according to this equation (5) and evaporation estimation according to the equation (7), i.e. ignoring the artesian discharge then aside from the hydrogeological absurdity of such an approach to the solution of this problem it would lead to the average perennial evaporation value increase of 6 — 13%, which in the absolute expression corresponds to the layer of 32 — 76 mm a year (table 1).

The perennial water balance maps of a territory should be made having in view geostructural and hydrogeological conditions of river basins and in general contain not three (as in all modern maps) but *four* isoline systems: *precipitation rate isolines* (X_0), *river discharge rates* (Y_0), *evaporation rate* (Z_0) *and infiltration rate into the depth water-bearing horizons* ($+ W_0$) *or artesian discharge rates* (supply) ($- W_0$) *in the river basin.* If necessary the river discharge may be devided into *surface* (Yo S) and *ground* one (Y_0^G).

TABLE 1

The complete average perrennial water balance of the supply area of the Dnieper-Donetz artesian basin.

The river basin	Circulation alignment	Water-collecting area km²	Precipitations (X_0) mm a year	Discharge								Evaporation Z_0		Total infiltration for groundwaters level ($I_0 = Y_0^C + Y_0^A$)	
				General (Y_0)		Including									
						Surface (Y_0^S)		Ground (Y_0^G)		Artesian (Y_0^A)					
				mm. per year	Percentage of X_0	mm. per year	Percentage of X_0	mm. per year	Percentage of X_0	mm. per year	Percentage of X_0	mm per year	Percentage of X_0	mm. per year	Percentage of X_0
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Soge	Gomel	38860	594	208,0	35,0	94,2	15,8	79,3	13,4	34,5	5,8	386	65,0	113,8	19,2
Desna	Vishenki	37620	581	197,0	33,9	87,6	15,1	73,4	12,6	36,0	6,2	384	66.1	109,4	18,8
Snov, Ubed and others	Tschors and others	11160	588	203,0	34,5	90,7	15,4	76,3	13,0	36,0	6,1	385	65,5	112,3	19,1
Seim	Mutino	25560	549	179,0	32,6	68,3	12,4	48,7	8,9	62,0	11,3	370	67,4	110,7	20,2
Psel	Sumi	7770	530	133,0	25,1	71,9	13,6	29,0	5,5	32,1	6,0	397	74,9	61,1	11,5
Vorskla	Kosinka	1870	527	129,0	24,5	67,1*)	12,8	15,9*)	3,0	46,0	8,7	398	75,5	61,9	11,7
Vorsklitza and others	upper reaches	3060	528	131,0	24,8	69,5	13,2	22,5	4,2	39,0	7,4	397	75,2	61,5	11,6
The North Donetz (without the river Moze basin)	Zmiev	14820	498	96,0	19,3	57,9	11,6	30,2	6,0	8,0	1,6	402	80,7	38,1	7,6
Oskol	Kypyansk	12720	500	99,0	19,8	58,2	11,6	36,4	7,3	4,4	0,9	401	80,2	40,8	8,2
Tim, Kshen, Oljim	upper reaches	4660	537	171,0	31,8	112,0	20,8	49,0	9,1	10,0	1,9	366	68,2	59,0	11,0

(*) The surface and ground discharge are taken according Krupetz alignment data.

The complex approach to the making of water balance scheme will put an end to the differences which still exist in the study of land surface and underground waters. The water balance maps according to the above mentioned principle will bind together the earth's water and promote particularization of all the elements of water balance. They will find wide application not only in geophysics but also in hydrology as well, while the existing water balance maps with their system of three isolines cannot be used for studying depth underground water balance and are quite wrong from the hydrogeological standpoint.

The further advent in studying water balance is undoubtedly associated with this new approach to the solution of this problem. It is guaranteed by the noticeable successes of geophysicists in making estimations more detailed and by measuring separate elements of water balance in nature (especially natural evaporation), and by the rapid progress in studying hydrology of this country.

VI. On the Actual Speed of Underground Water Movement and on the Change of Water in the Dnieper-Donetz artesian basin.

14. The definition of actual speed of water movement and the water-change time in large artesian basins is of a considerable theoretical and practical interest. On the basis of the data of artesian waters general discharge value found with the water balance method (section IV «B») and due to the hydraulic cross-section of artesian basin it became possible to compute the average actual speed of water movement in sedimentary beds (u) which proved to be equal to $u \simeq 0.01$ m per day.

Taking as the main discharge area the movement distance from the supply centre in the Seim basin to the Dnieper valley (fig. 13) which is equal to 360 km we find that the running time of water particle is approximately equal to 100,000 years.

If all water discharge will be at the expence of sandy and easily permeable rocks which occupy about 1/3 of the cross-section the running time of water particle will be lessened three times and make 33000 years.

The estimations of different litho-stratigraphical complexes have shown the following running time of water particles from the supply area to that of discharge — for Jurassic sands as 26000 years, for Lower Cretaceous and Senoman sand layers as 21.000 years and for Buchaksko-Kanevian sands as 25.000 years respectively.

If the total geological reserves of artesian basin underground waters be divided into the value of annual inflow of atmospheric waters from the supply area we shall get waterchange duration. Corresponding estimations have shown that the mean time of waterchange for all the artesian basin is equal to 35.000 years. For different litho-stratigraphical complexes water-change duration vary about 107.000 years (for Devon), 14000 years (for Paleogene). The main water bearing horizons resources which are used for water-supply, that is, Jurassic and Senoman sand — are correspondingly renewed in the period of 28.000 and 19.000 years. Hence the Dnieper-Donetz artesian basin water is successfully used as drinking water supply of recent atmospheric origin.

Water-balance estimations have shown that artesian water natural resources for all the main water-bearing horizons greatly exceed the existing selection for water supply aims. The exploitation of the Dnieper-Donetz artesian waters may be increased for different water-bearing horizons not less than 4 — 10 times in comparison with the existing water-collecting level without any risk of depletion of water-bearing horizons. This conclusion gives important directions to the practical exploitation of artesian basin waters.

THE DETERMINATION OF THE GEO-HYDROLOGICAL CONSTANTS FOR THE DUNE-WATER CATCHMENT-AREA OF AMSTERDAM

L. HUISMAN

New Works engineer Municipal Waterworks of Amsterdam

SUMMARY

The geo-hydrological structure of the Amsterdam dune-water catchment-area can be schematically represented as a water-bearing formation, shut off at the bottom by an impermeable basis and divided in different aquifers by one or two less pervious layers.

The determination of the geo-hydrological constants consequently comprises the determination of the permeability of the different sand-layers in horizontal direction and the determination of the resistance against the vertical water-movement of the less pervious layers of clay and loam.

These determinations cannot be done in any order. The article shows the order that has to be chosen and how the geo-hydrological constants can be determined by means of balances of water-movements, the verification of measured potential lines of certain parts of the catchment-area and the analysis of the results of test-pumpings on different wells for the winning of artesian water.

The calculated values of the geo-hydrological constants may be checked by computating the flow-pattern for the whole of the catchment-area.

The catchment-area of the city of Amsterdam is situated along the North Sea-coast, south of Zandvoort over a length of approximately 10 kilometres. Figure 1

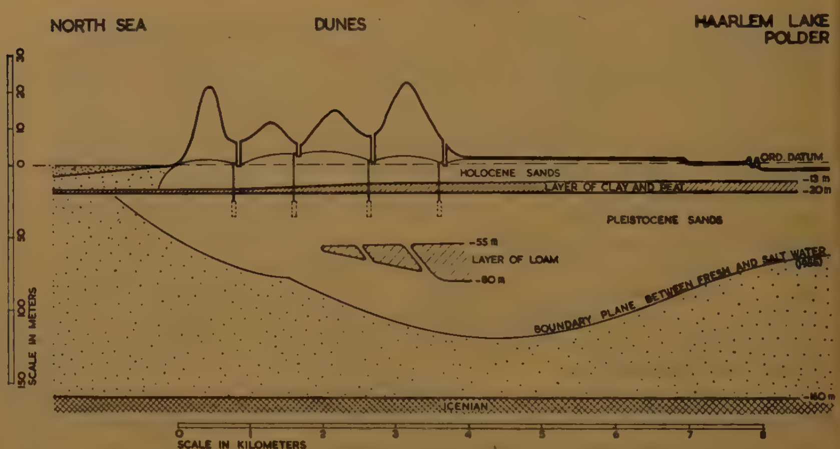


Fig. 1

shows a cross-section of this area perpendicular to the coast. The dune-area is about 4 kilometres wide and the dunes have a height of 5 to 10 metres + O.D. (Amsterdam ordnance datum is about 0.15 metres above mean sea-level) with some tops at 30

metres + O.D. The water-level in this area varies considerably and has an average height of 1 metre + O.D., the highest level being 4 metres + O.D. On the westside the catchment-area is bounded by the North Sea , on the eastside by a 4 kilometres broad strip of fairly flat land with a groundwater-level varying from 1 metre + to 0.6 metre — O.D. East of this strip lies the reclaimed Haarlem-lake with a groundwater-level of 5 metres — O.D.

In the catchment-area a graet number of borings have been constructed from which the geological structure can be concluded. As far as the water-movement in the sub-soil is concerned chiefly three layers can be distinguished in this area: the comparatively fine holocene sand-formation between ground-level and 13 metres — O.D., the less pervious clay- and peat-layers between 13 metres—and 20 metres—O.D. and the for the greater part coarse pleistocene sand-formation between 20 metres—and 160 metres—O.D. Then the Icenian stretches below 160 metres—O.D., a marine formation of very fine and silty sand, so fine and containing so much silt that it may be considered the basis of the water-bearing formation.

From water-level observations it appears that the hydrological profile is very similar to the geological. In hydrological respect the dunes consist of a water-bearing sand-formation, shut off at the bottom by the Icenian and divided into two parts by the so-called clay-layer between 13 metres—and 20 metres—O.D. The water above the clay-layer is phreatic water, while the water under the clay-layer is artesian. In the north-eastern part of the catchment-area though is another less pervious layer, the so-called loam-layer, situated roughly between 55 metres—and 80 metres—O.D., which in its turn—strictly speaking—divides the pleistocene formation into two parts. In contrast with the clay-layer, which is found uninterruptedly through the whole of the catchment-area, this loam-layer is only local and with many breaks and openings, so that a continuous separation in the hydrological sense can hardly be spoken of. For the water-movement as a whole the loam-layer has therefore hardly any significance although it does make its influence felt in the case of local abstactions.

In the pleistocene sand-formation between 20 metres—and 160 metres—O.D. however a distinction has to be made between fresh and salt water. Thousands of years ago the entire sub-soil was filled with salt water. In figure 1 this salt water is marked with dots. The fresh rain-water did not mix with the salt water in the sub-soil but floated on it and thus in the course of many centuries a fresh water-body was formed. Under the catchment-area this body reached its greatest depth at 120 metres—O.D. while kilometres of fresh water-tongues stretched under the sea and under the inward land. Figure 1 shows the shape of the fresh water-body as it is at present, but which has receded considerably, especially at the sea-side, as a result of the water-abstraction.

The abstraction of water in the catchment-area is done in two ways. The water above the clay-layer is abstracted by means of open canals with a total length of 37 kilometres, the water under the clay-layers through approximately 400 wells with screens between 25 metres and 35 metres — O.D. In total about 30 million m^3/year is abstracted of which about 1/3 is phreatic water and 2/3 artesian water. This division is not constant, but depends on precipitation and evapotranspiration. It is chosen in such a way that the water-level in the water-body above the clay-layer remains constant. The replenishment of the dune-water catchment-area exclusively results from infiltrating rain-water. After deducting the evapotranspiration this quantity amounts to an average of 17 million m^3/year, so that yearly 13 million m^3/year is taken from the fresh waterstock in the deep sub-soil. As a result the boundary-plane between fresh and salt water has risen 0.8 metre/year (in 1957 this exhaustion shall be put to an end by infiltrating 20 million m^3/year of river-water into this area).

In order to be able to give a full description of the geo-hydrological profile of

the catchment-area of the Amsterdam Water Works the values have to be determined of:

1. the permeability in horizontal direction of the sand-formation above the clay-layer;
2. the resistance against vertical water-movement of the clay-layer;
3. the permeability in horizontal direction of the sand-formation between the clay-layer and the loam-layer;

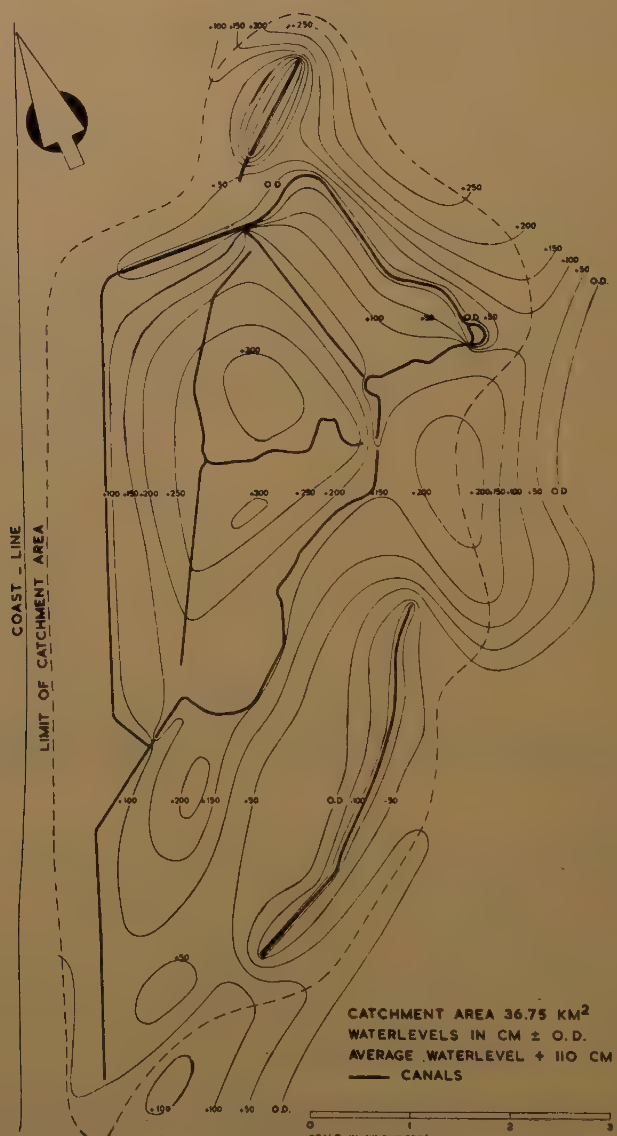


Fig. 2

4. the resistance against vertical water-movement of the loam-layer;
5. the permeability in horizontal direction of the sand-formation between the loam-layer and the Icenian.

Of these quantities not only the average values have to be determined but—as far as necessary—also the variation across the whole area. For the determination of the values of the geo-hydrological constants several data are at disposal. The

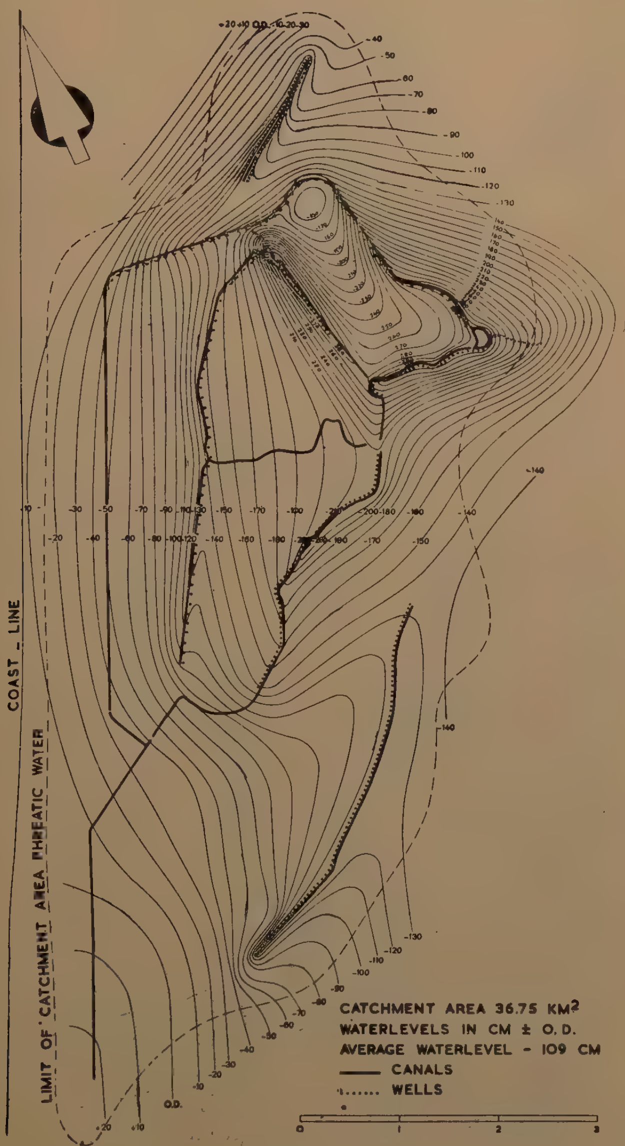


Fig. 3

quantity of the precipitation minus evapotranspiration is known from long series of lysimeter-observations. The head of the water above the clay-layer as well as in the different aquifers underneath is being measured already for many years in a great number of gauging wells and worked up into isohyps-maps of which figures 2 up to 5 inclusive set an example. The level of the boundary-plane (fig. 6) between fresh and salt water can be determined from the difference in head between the deep fresh

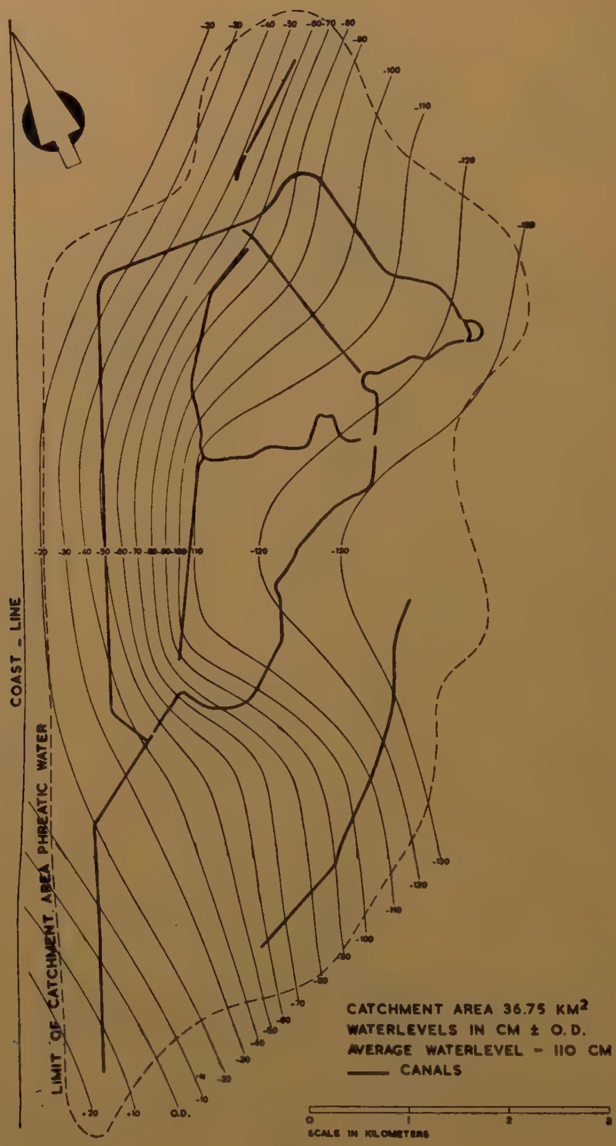


Fig. 4

and the deep salt water (specific gravity fresh water 1000 kg/m^3, salt water 1020 kg/m^3) and can directly be measured from the Cl'-content of the water in observation-wells at different depths. Test-pumpings have been carried out on several wells for the winning of artesian water. The propagation of the tide into the artesian water under the clay-layer has been measured in the dune-area and several other tests have been executed.

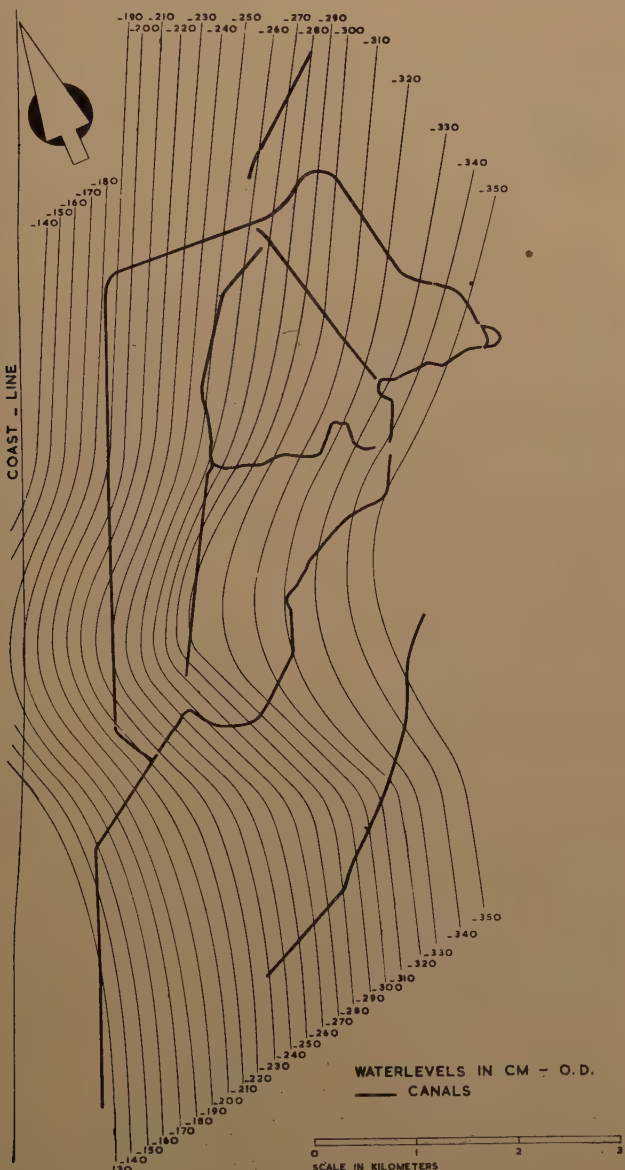


Fig. 5

The determination of the values of the geo-hydrological constants cannot however be done in any order. For the calculation of the value of a certain quantity generally the knowledge of the values of the other constants is essential. These are however still unknown. Directly only the average resistance of the clay-layer against infiltration of phreatic water into the formation underneath can be calculated. This resistance can be defined as the ratio between the drop of potential that occurs to

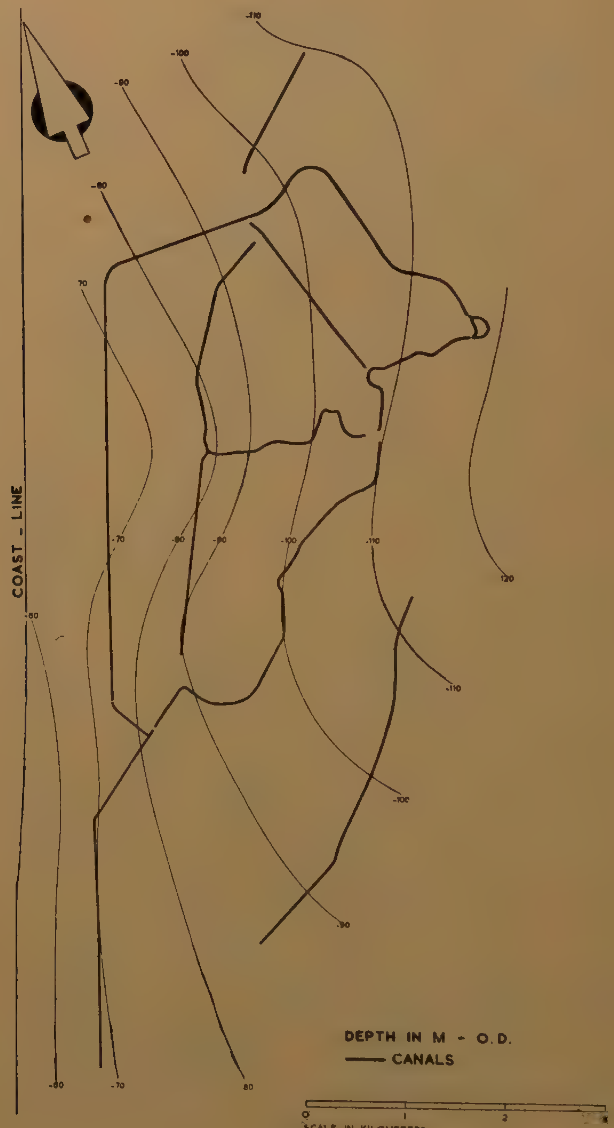


Fig. 6

infiltration and the quantity of water which infiltrates per unit of surface and of time, in formula $c = \frac{\Delta h}{q}$, with $q = \frac{Q}{F}$, in which c is the resistance of the clay-layers against vertical water-movement, Q the quantity infiltrating per unit time, F the surface over which the infiltration is at stake and Δh the drop, i.e. the difference between the average water-level above and under the clay-layer. When q is expressed in m^3/year and Δh in metres, then the value of c follows in years. The quantity of q can be found from the water-balance of the formation above the clay-layer. In figure 2 the limit of the catchment-area is drawn, that is to say the geometrical locus of the points with a phreatic water slope of nil. Through this line no water in the formation above the clay-layer flows into the catchment-area neither through this line outward. Hence the balance for the phreatic water of the catchment area is :

replenishment through rainfall = phreatic water-abstraction + storage + infiltration through the clay-layer

The replenishment through the rain is known from the surface of the catchment-area (F) and from the precipitation minus evapotranspiration according to the lysimeter-observations. The amount of abstracted phreatic water is measured. For the determination of the storage isohyps-maps of the phreatic water-table have to be drawn for beginning and end of the period concerned; the rise of the average water-level multiplied by the surface of the catchment-area and by the percentage of pores, as determined by laboratory-tests on soil-samples, give the storage. The infiltration Q through the clay-layer then follows as closing entry of this balance. The drop Δh can be determined by drawing average isohyps-maps for the period concerned of the water above and under the clay-layer and by calculating from this the average level of the phreatic water and the artesian water for the catchment-area. For the period 1930-1946 the catchment-area comprised 37.0 km^2. Precipitation minus evapotranspiration amounted to an average of 460 mm/year corresponding with a replenishment of the catchment-area of 17 million m^3/year. In the 17-year period 1930-1946 the average phreatic water-level in the catchment-area rose 0.2 metre with a pores space of 40%, corresponding with a storage of 0.2 million m^3/year. From the catchment-area an average of 10.8 million m^3/year was abstracted by means of the open canals. As closing entry on the balance thus a quantity Q of 6.0 million m^3/year remains for infiltration through the clay-layer inside the catchment-area, from which follows that $q = 0.16$ metre/year. During the period concerned the average phreatic water-level in the catchment-area was 1.24 metre + O.D., the average artesian water-level 0.57 metre—O.D., so that the infiltration occurred to a drop of 1.81 metre. From the ratio between Δh and q a resistance of the clay-layer c follows of 11 years or 4000 days. This value represents the average value of the resistance over the entire surface of the catchment-area. In order to calculate the variation of this resistance over the area water-balances have to be made for smaller sectors. Then however the outflow to the sides plays an important role and this outflow can only then be calculated when the permeability in horizontal direction of the formation above the clay-layer is known.

The flow of water in the formation above the clay-layer towards the canals is accompanied by a slope S, which, according to Darcy's law, equals $\frac{Q}{kD}$, in which Q is the flow per running metre and kD the permeability in horizontal direction of the upper dune sand-formation. When Q is known, the value of kD could be calculated by measuring S from the isohyps-maps. The value of Q depends on precipitation minus evapotranspiration, known already from lysimeter-observations on different

spots and on the infiltration through the clay-layer. The latter depends on the difference in head between the water above and under the clay-layer, to be measured from isohyps-maps and from the value of the resistance of the part of the clay-layer concerned. This local resistance is however still unknown, only the average value over the whole of the catchment-area is computed at 11 years or 4000 days. When however for the computation of the permeability kD places are chosen where the phreatic water-level and the artesian water-level differ very little, then the average value of the resistance of the clay-layer gives sufficient approximation of the value of this local resistance for the determination of the permeability. The average value can in this way also with sufficient approximation be applied to those places where according to the results of geological borings the clay-layer has about the average structure, as is the case in the northern part of the catchment-area. When for these places the observed slope of the phreatic water-table is checked, then the value of kD can be determined. The height of the water-table can be described with the formula

$$h = C_1 . e^{-\frac{x}{\sqrt{kD.c}}} + C_2 . e^{+\frac{x}{\sqrt{kD.c}}} + N.c + \varphi$$

in which h is the water-level, N precipitation minus evapotranspiration, c the resistance of the clay-layer fixed at 4000 days and φ the head of the artesian water under the clay-layer. C_1 and C_2 are integration constants, e.g. determinable from the given water-levels in the canals, that form the border of the area under consideration. The value of kD then follows for instance from the highest water-level between the two canals. For the value of kD is found with very little variation:

kD = 100 + n. 12 m²/day in which n is the number of metres the waterlevel is + O.D. The dunes are an aeolian formation and therefore of a very equable structure. This also appears from the results of the geological borings. The above calculated value of the permeability in horizontal direction may therefore be applied unchanged over the whole of the catchment-area.

Since the permeability in horizontal direction of the sand-formation above the clay-layer is known, the water-balance of any part of this formation, with outflow to the sides, can be made up and from that the quantity of the local infiltration can be calculated. The ratio between the drop in potential occurring to infiltration and the strength of this infiltration gives the value of the local resistance of the clay-layer. In order to obtain a systematic calculation a network of regular hexagons with sides of 200 metres was laid over the whole of the catchment-area. Of each of those hexagons, which are not crossed by an open canal, the waterbalance is made up, the drop occurring to the infiltration measured and thus the resistance of the clay-layer determined as an average for each hexagon with a surface of 0.1 km². The result of this calculation for larger hexagons with a surface of 1.2 km² each, is given in figure 7. It appears that the resistance of the clay-layer against vertical water-movement varies from 30 years in the north-eastern part of the catchment-area to 2 years in the southern and western part, entirely corresponding with the results of the geological borings, which in the north-eastern part brought to light a layer of fat clay of a thickness of some metres, decreasing to the south and west to only a few centimetres of sandy clay. In order to check the result given in figure 7 the infiltration over the whole of the catchment-area is calculated with the help of these resistances over the period 1930-1946 from the average isohyps-maps of the water above and under the clay-layer. The correspondence between the infiltration calculated in this way and the infiltration determined from the water-balance of the phreatic water of 6 million m³/year, as mentioned above, turned out to be satisfactory.

The determination of the transmissibility in horizontal direction of the pleistocene formation under the clay-layer can best be carried out through analysis of the

results obtained by test-pumping on a well for the abstraction of artesian water. In the southern and western part of the catchment-area, where no loam-layer exists, the potential-decrease in the artesian water at a distance x from the well, which is pumped with a constant capacity Q can be determined by the following formula

$$\varphi = \frac{Q}{4kD} \cdot H_0 \left(\frac{X}{\sqrt{kDc}}\right)$$

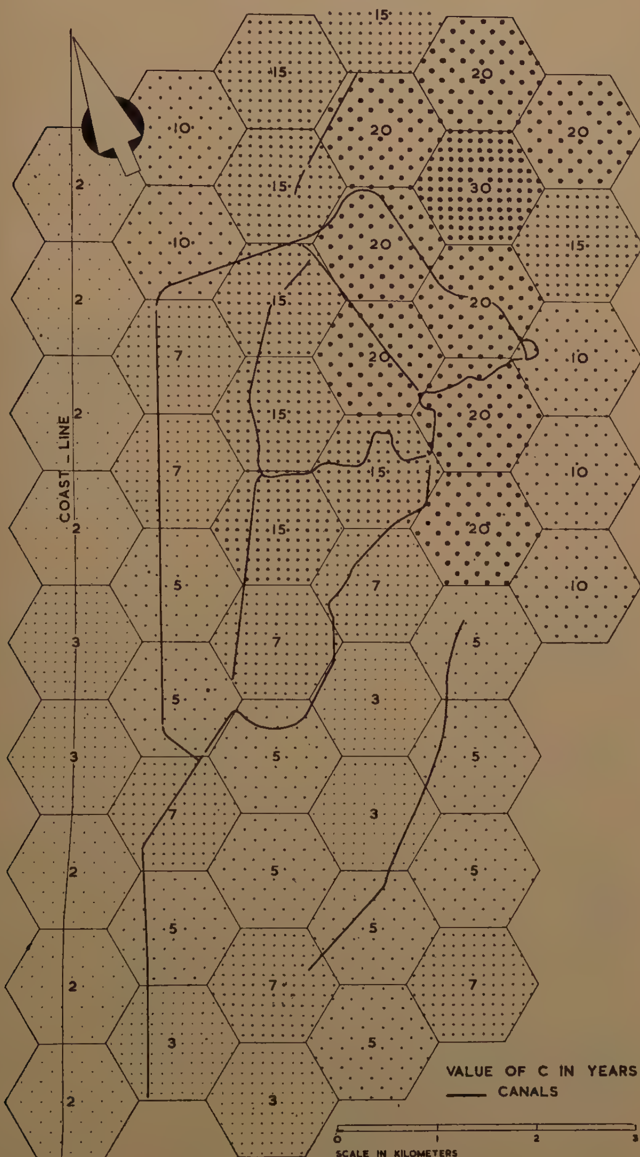


Fig. 7

In this formula H_0 is a Besselfunction, kD the transmissibility wanted and c the resistance of the less pervious clay-layer, which shuts off the pleistocene formation at the top. When on a diagram with logarithmic division on both sides the measured potential-decrease φ is plotted against the distance x and when an H_0 (α) curve, drawn on transparent paper on the same scale, is moved without turning until it covers the plotted points as well as possible (fig. 8), then the vertical movement gives the value of the transmissibility kD and the horizontal movement the value of the factor $\sqrt{kDc}$ and consequently the resistance c of the clay-layer. An accurate determination of the values of the geo-hydrological constants of the pleistocene sand-formation cannot however be obtained in this way. The pumped well does not quite pierce through the full height of the water-bearing formation. At a short distance from the well the potential-decrease is consequently measured higher than should follow from the formula. The artesian wells have only a limited capacity, normally 10 m^3/hour at the utmost, as a result of which at a greater distance from the pumped well the potential-decrease is small and cannot be determined exactly. Besides variations in sea-level, change of the abstraction of the neighbouring wells, variations in the phreatic water-table, fluctuations of the barometer-pressure etc. make their

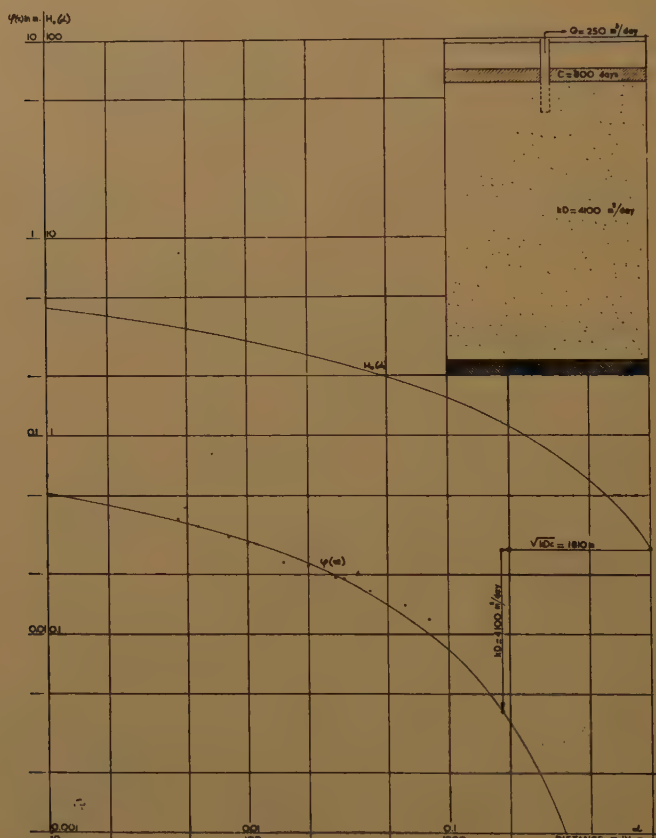


Fig. 8

interfering influence felt. The accuracy of the determination of the transmissibility can be increased by considering the value of the resistance of the less pervious layer not as an unknown factor in the analysis of the test-pumping but by using the value following from figure 7. In the southern and western part of the catchment-area in this way a value for the transmissibility in horizontal direction for the sand-formation between clay-layer and Icenian is found of approximately 4000 m²/day. A slightly smaller and especially a somewhat higher value would however not be in contradiction with the results of the test-pumpings. In the north-eastern part of the catchment-area the loam-layer divides the pleistocene formation into two parts. The screen in the upper part is here situated between two less pervious layers and for the potential-decrease φ at a distance x from such a well, which is pumped with a constant capacity Q, the following formula hold good:

$$\varphi_1 = \frac{Q}{4k_1D_1} \cdot \frac{\lambda_1 - \alpha_2}{\lambda_1 - \lambda_2} \cdot H_0(\sqrt{\lambda_1 x}) + \frac{Q}{4k_1D_1} \cdot \frac{\alpha_2 - \lambda_2}{\lambda_1 - \lambda_2} \cdot H_0(\sqrt{\lambda_2 x})$$

$$\varphi_2 = \frac{Q}{4k_1D_1} \cdot \frac{\alpha_2}{\lambda_1 - \lambda_2} \left(H_0(\sqrt{\lambda_2 x}) - H_0(\sqrt{\lambda_1 x}) \right)$$

in which φ_1 represents the potential-decrease in the upper and φ_2 in the lower pleistocene sand-layer. H_0 is again the Besselfunction, while the constants used in this formula are determined by the relations

$$\begin{matrix}\lambda_1 \\ \lambda_2\end{matrix} = \tfrac{1}{2}\left[\alpha_1 + \alpha_2 + \beta_1 \pm \sqrt{(\alpha_1 + \alpha_2 + \beta_1)^2 - 4\alpha_1\alpha_2}\right]$$

$$\alpha_1 = \frac{1}{k_1D_1c_1} \qquad \alpha_2 = \frac{1}{k_2D_2c_2} \qquad \beta_1 = \frac{1}{k_1D_1c_2}$$

in which k_1D_1 represents the transmissibility in horizontal direction of the sand-formation between clay-layer and loam-layer, k_2D_2 the one between loam-layer and Icenian, c_1 the resistance against vertical movement of the clay-layer and c_2 that of the loam-layer. Also in this case an analysis of the test-pumping, a determination of the values of the geo-hydrological constants is very well possible. The result is however less accurate, of which figure 9 gives an example. The analysis here is also much more complicated and would in the scope of this article require too much space to be described in detail. With the assumed values of the resistance of the clay-layer in figure 7 the analysis of test-pumpings on a great number of wells gives for the resistance against vertical water-movement of the loam-layer a value that varied from place to place from 0 — 200 days, a very small number indeed. The transmissibility of the sand-formation between clay-layer and loam-layer varied from spot to spot between 500 and 1500 m²/day and of the sand-formation between loam-layer and Icenian from 3000 — 4000 m²/day. The total transmissibility of the entire formation between clay-layer and Icenian fluctuated between 4000 and 5000 m²/day, although a somewhat smaller and especially a greater value could very well be possible. Through analysis of the propagation of the tide in the artesian water below the clay-layer near the coast line it is possible to calculate the value of the factor $\sqrt{kDc}$ in that area. The value thus found is however considerably smaller than follows from test-pumpings and water-balances. It is not further taken into consideration.

In order to check the values found above of the geo-hydrological constants the water-balance of the pleistocene sand-formation underneath the clay-layer can

be made up. The inflow of this formation by downward infiltration through the clay-layer is known from the phreatic water-balance. The water-abstraction by means of wells is measured. The amount of outflow to the sides can be determined with the help of the slopes, to be measured from the isohyps-maps. The formation under the clay-layer is completely filled with water, so that the total of all inflow and outflow has to be nil. With the above mentioned constants this turns out not to be the case with all possible hydrological situations. A balanced account of all those cases can however be obtained by increasing the transmissibility in horizontal direction of

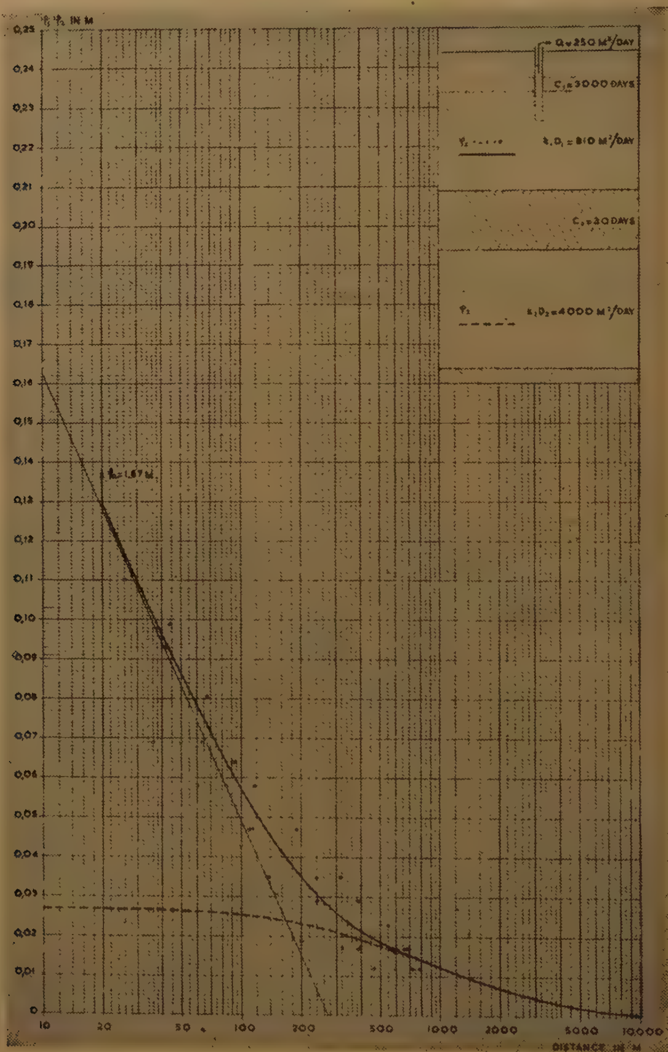


Fig. 9

1850

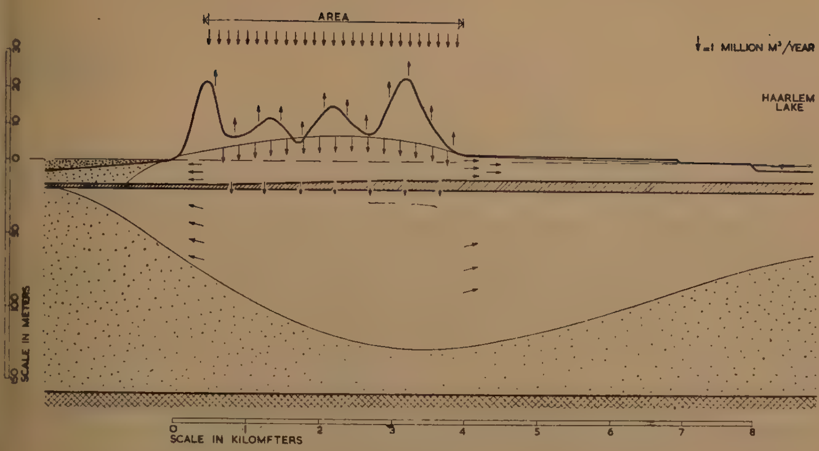


Fig. 10

1955

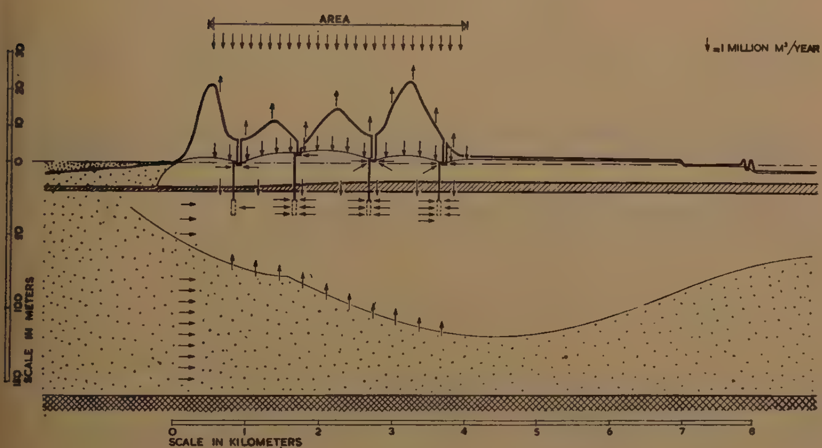


Fig. 11

the sand-formation between clay-layer and Icenian on the westside of the catchment area to 4500 m²/day and on the eastside to 5500 m²/day, here sub-divided into a value of 1500 m²/day for the formation between clay-layer and loam-layer and 4000 m²/day for the formation between loam-layer and Icenian. These values are not in contradiction with those found with the analysis of the results of the test-pumpings. From the balances of the artesian fresh and the artesian salt water separately the rise of the fresh-salt water boundary-plane can be calculated, which—with the chosen

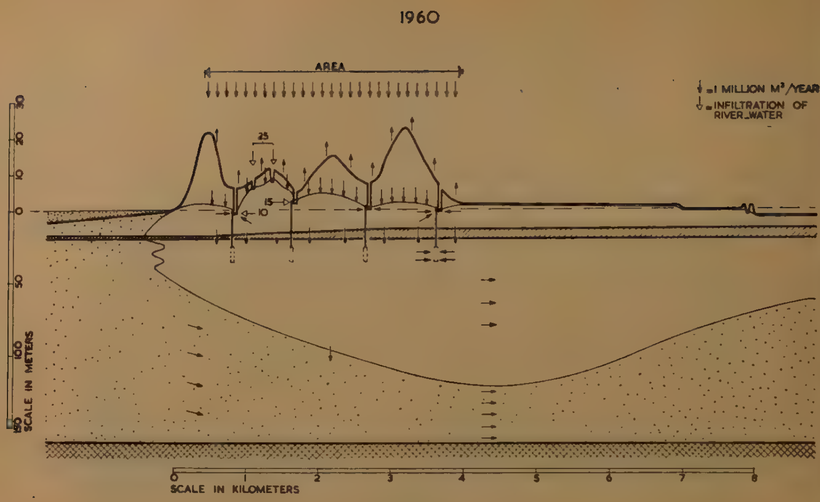


Fig. 12

values of the horizontal transmissibilities—is then in good agreement with the measured rise.

The result of the calculations mentioned above is not so much of importance because now the values of the geo-hydrological constants itself are known, but especially because with them the flow-pattern in the catchment-area can be analysed in detail. Figure 10 shows the computed flow in 1850, when water was not yet abstracted and the Haarlem-lake had not yet been reclaimed. Figure 11 shows the position of 1955 with an abstraction more than twice as much as the safe yield. Figure 12 shows how this position can be improved by an extra replenishment through infiltration of river-water into the dunes.

A FIELD METHOD FOR MEASURING THE PERMEABILITY OF SANDSTONE CORES

N. S. BOULTON & G. S. DHILLON
University of Sheffield

SUMMARY

A simple method is described for measuring the hydraulic permeability of sandstone cores in the field. A small vertical hole is drilled to a limited depth below the surface of the core and the upper part of its length is provided with an impermeable lining. Water is fed to the hole so as to maintain a constant hydraulic head in it. When a steady state of flow is established, the volume of water entering per unit time and the head are recorded. From these readings the permeability of the sandstone is easily obtained using a very simple formula. A coefficient θ in the formula, which depends upon the flow pattern, has been determined by an approximate theoretical equation. In particular cases its value has been found by more exact numerical methods. Values of θ have also been determined experimentally.

The method is applicable in principle to permeability determinations of cemented or uncemented sands *in situ* which are above the water-table, but the technique of such applications is not discussed in this paper.

A simple extension of the method is described for the determination of separate horizontal and vertical permeabilities in the case when the sandstone core is anisotropic.

By providing a simple means of determining the variation of permeability with depth in a bore-hole, the method should prove a useful addition to the field pumping test for investigating hydrological conditions in an aquifer.

Introduction

The permeability test to be described originated in an attempt to obtain a simple method which could be used in the field to determine the hydraulic permeability of sandstone cores as they are laid out after boring by the rotary method. The most reliable permeability determination for water supply purposes is usually provided by the field pumping test. This gives an average value for a fairly large block of the aquifer. Before, however, the hydrological characteristics of an area can be reliably interpreted, the degree to which the aquifer is heterogeneous must be known, as recently pointed out by Ineson ([1]). Information on this point is provided by horizontal and vertical permeability measurements on core samples at a number of depths in the aquifer. If the permeability varies little with depth and if the average value agrees approximately with the value found from a pumping test, it would seem reasonable to assume that the aquifer is fairly homogeneous; in this case the usual theory based on Darcy's Law may be applied with confidence. On the other hand a large difference between the permeability as measured in the cores and as found from a pumping test indicates that the aquifer is heterogeneous and perhaps, also, that much of the flow to the well is occurring in fissures. From such considerations as these it seems likely that a quick and simple method of determining the permeability of cores may prove useful.

The proposed method can also be adapted to determine the permeability of cemented or uncemented sands *in situ* which are above the water-table. In this paper, however, only a field test suitable for sandstone cores is discussed in detail.

Field methods for determining the permeability of saturated soil below the water-

([1]) The references are given on p. 192.

table have been developed by Kirkham (2) and Childs (3). A method which is applicable above the water-table has been described by Matsuo (4). This method consists in measuring the seepage under gravity from a trench or pool formed in the surface of the medium. From the flow-pattern as determined theoretically or experimentally the relationship between the rate of seepage and the permeability is known. The field technique involved does not, however, appear to be very convenient and the available range of pressure head where the water enters the medium is very limited

Principles of the method.

A vertical cylindrical hole of radius r_0 is drilled in the sandstone to a depth l_2 below the surface and provided with an impermeable lining for a smaller depth l_1 (Fig. 1). A transparent vertical tube is joined to the top of the lining tube. Water

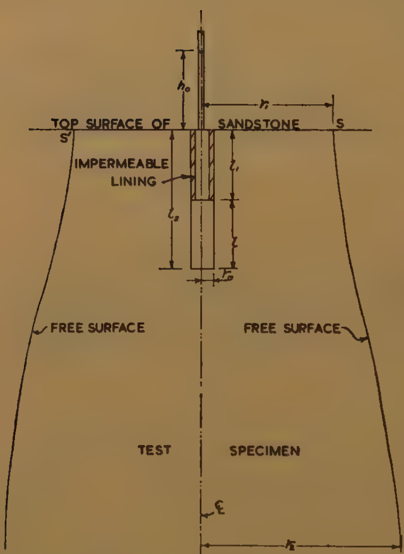


Fig. 1 — Profile of test specimen showing drill-hole, region of seepage flow and symbols used.

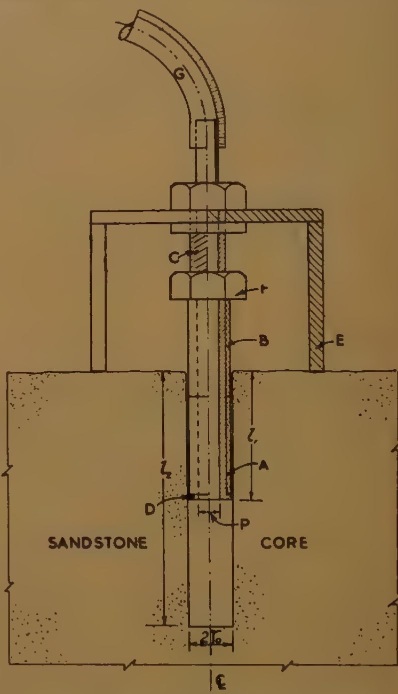


Fig. 4 — Field apparatus for lining upper part of drill-hole.

is fed into the open end at a rate which maintains a constant level at the desired height h_0 above the sandstone surface. After a sufficient time interval* for the flow to become steady, the volume of water Q flowing into the tube per unit time and the head h_0 are recorded. The hydraulic permeability is then easily calculated from the relationship between Q and h_0 established in the next section of this paper.

The region of saturated seepage flow, which is symmetrical about the axis of

* The time interval is reduced by first saturating the core with water.

the drill-hole, may have a curved lateral boundary of two types. If the head h_0 is greater than a certain critical value, depending on the values of l_1, l_2 and r_0, seepage occurs from the upper surface of the sandstone within a circle of radius r_1. Joining this circle there is a curved boundary to the flow which (neglecting capillary rise) is a stream surface and also a surface of constant atmospheric pressure. If, however, h_0 is less than the critical value there is no upper seepage surface and the free surface joins the lined part of the drill-hole. For reasons which are explained later, the most suitable head h_0 is above the critical value so that the free surface always extends to the top of the sandstone.

At a depth which is large compared with l_2 the profile of the free surface is practically vertical at some limiting radius r_2 from the axis. It is assumed that the sandstone specimen is sufficiently large for these boundary conditions to occur without interruption.

The head-inflow relationship

An exact solution for the flow pattern by mathematical analysis is not available. Hence the procedure has been to obtain an approximate equation for the head in terms of the inflow by wellknown potential theory. This theory has the advantage that the head-inflow equation can easily be evaluated numerically for different heads and dimensions of drill-hole, and the radii r_1 and r_2 (Fig. 1) can also be evaluated. The theory fails, however, to satisfy some of the actual boundary conditions; it is therefore necessary to examine its accuracy by comparing it in particular cases with less approximate solutions, obtained by rather lengthy numerical methods. A correction factor can thus be introduced into the approximate equation.

Laboratory tests which have been made with loose sand in a tank provide an experimental determination of the head-inflow relationship which is compared with the theoretical results.

Approximate Theory.

It is assumed that the flow from the drill-hole may be represented by a line «source» of uniform intensity along the axis of the unlined part of the drill-hole. By introducing a negative image of this source, placed symmetrically with respect to the top surface, the condition for constant (atmospheric) pressure on this surface is satisfied. The superposition on this flow of a uniform downward vertical flow under unit hydraulic gradient satisfies the condition of constant atmospheric pressure at large distances from the drill-hole. The required boundary conditions are however incorrectly represented in three respects. The hydraulic head (pressure plus potential head) at the unlined surface of the drill-hole is not constant as it should be; the line source gives a small flow across the lined part of the drill-hole and the requirements at the free-surface are not accurately satisfied.

In order to determine the value of h_0, the variable head is averaged over the unlined length l of the drill-hole. The detailed analysis, which is straight forward and is here omitted, leads to the equation

$$h_0 + \tfrac{1}{2}(l_1 + l_2) = \frac{Q}{kl}\left[\frac{1}{4\pi(b-a)}\left\{2(b-a)\sinh^{-1}(b-a)\right.\right.$$
$$+ 2(b+a)\sinh^{-1}(b+a) - 2b\sinh^{-1}2b - 2a\sinh^{-1}2a - 2\sqrt{1+(b-a)^2}$$
$$\left.\left. - 2\sqrt{1+(b+a)^2} + \sqrt{1+(2b)^2} + \sqrt{1+(2a)^2} + 2\right\}\right] \qquad (1)$$

In equation (1) $a = l_1/r_0$, $b = l_2/r_0$ and k is the permeability coefficient* defined by $v = ki$, where v is the discharge velocity and i the hydraulic gradient.

It is convenient to write

$$h = h_0 + \tfrac{1}{2}(l_1 + l_2).$$

Thus h is the pressure head at the centre of the unlined part of the drill-hole.

Also, denoting the dimensionless expression within square bracktes in equation (1) by θ, this equation takes the simple form

$$h = \frac{Q\theta}{kl}$$

whence

$$k = \frac{Q\theta}{hl} \qquad \text{(2)}$$

The quantity θ is a function only of the relative dimensions a and b of the drill-hole and its lining. Owing, however, to the existence of a free surface which moves with change of head—a factor ignored in the derivation of equation (1)—θ is not theoretically independent of h, though it may prove to be constant for practical purposes.

When suitable dimensions for the drill-hole have been chosen, θ can be calculated once for all, and thus the permeability coefficient k is very easily found from equation (2) for values of Q and h observed in a field test.

More Accurate Determinations of θ

For the particular drill-hole proportions $a = 6$, $b = 12$, and for a head $h_0 = 100r_0$, the flow pattern was determined by the method of relaxation. This method enables the boundary conditions, including those at the free surface and drill-hole, to be correctly represented, errors arising only from the finite size of the relaxation net. It is therefore suitable for testing the accuracy of equation (1) based on the approximate theory. The relaxation solution shows that θ as given by equation (1) is 13 per cent too large.

A potential solution which very nearly satisfies the correct boundary conditions at the drill-hole, but which, like equation (1), does not accurately satisfy the free surface conditions, has also been obtained for $a = 6$ and $b = 12$ and for a number of different heads. In this solution the distribution of a variable line source along the drill-hole axis is determined by the method of least squares, so as to satisfy the conditions for no flow across the lining and for constant head over the unlined part of the drill-hole. A value of θ only 2 per cent less than that given by the relaxation solution was obtained, thus confirming the accuracy of the method. For the range of head $9 \leqslant h/r_0 \leqslant 109$ the $Q - h$ relationship for the accurate potential solution is closely represented by a straight line passing throung the origin, showing that θ is very nearly constant for the range of head considered.

Tests in Sand Tank.

Of the theoretical solutions which have been described only the relaxation solution correctly represents the free surface boundary and this solution takes no account of the possible effect on the discharge of the capillary layer which normally occurs at a free surface in a granular medium. Therefore it was considered desirable to verify the values of θ obtained theoretically by carrying out tests in a sand tank which was 3 ft. 3 in. diameter and 6 feet high. The tank was filled with a graded sand

(*) Also called the hydraulic conductivity.

having a particle size of between 0.047 and 0.012 inch. The «drill-hole» was 3 inches diameter and 18 inches long and was lined for a depth of 9 inches with a metal pipe. To support the sand over the unlined length, a gravel liner was provided which was similar to that described by Childs ([5]), and having the merit of producing no potential jump at the surface of the drill-hole. The hydraulic head h in the drill-hole was provided by an overhead tank and the discharge Q of water from an outlet at the base of the sand-tank was measured. Care was taken to ensure that the flow was not large enough to cause the free surface to cut the sides of the tank. The permeability k for the sand as packed in the tank was determined independently of the drill-hole test by using the tank as a constant head vertical flow permeameter. Hence, by substituting the measured values of Q, k and h in equation (2), the value of θ was determined.

Numerical values of θ

The mean value of θ obtained by each method is shown in Column 1 of Table 1 for $a = 6$, $b = 12$. In Column 2 the maximum departure of a single determination from the mean is given as a percentage of the value in Column 1. The maximum and minimum values of h/r_0 are given in Column 3.

TABLE 1

	Column 1	Column 2	Column 3
Approximate potential solution	0.235	0.0	—
Accurate potential solution	0.203	0.6	19 — 109
Relaxation solution	0.207	—	109
Tests in sand-tank	0.197	3.0	26 — 36

The agreement of θ to within 2 per cent for the accurate potential solution and the relaxation solution suggests that the incorrect representation of the free surface in the former solution does not appreciably affect θ. However, there is a possibility of more important disagreement at the smaller heads in Table 1.

The value $\theta = 0.205$ is proposed as most likely to be correct for $a = 6$. $b = 12$.

For other values of a and b, θ may be found from the approximate potential solution and corrected by reducing it in the ratio $\frac{0.205}{0.235} = 0.872$ to allow for the error in this solution.

In Table 2 of the next section θ is required for $a = 6$, $b = 24$. Its value as calculated from equation (1) and multiplied by 0.872 is $\theta = 0.282$.

The value of θ from the sand tank differs from 0.205 by 4 per cent, a difference which could be accounted for by the uncertainty in the determination of k in these tests, which directly affects θ.

Selection of drill-hole dimensions and hydraulic head.

To minimize the error due to slight irregularities in the drill-hole, its diameter

should be as large as can be conveniently drilled in the field. For sandstone cores and an electrically driven drill, a diameter of 3/4-inch has been found suitable. Adopting this value, $r_0 = 3/8$-inch. The total length l_2 of the drill-hole must be sufficiently small as compared with the thickness of the sandstone specimen so that the lower boundary conditions assumed in the theoretical solution are satisfied, and the length must not be so great that the hole is difficult to drill. A length $l_2 = 4.5$ inches is suggested thus giving $b = l_2/r_0 = 12$.

The length l_1 of the lining and the head h to be used require special consideration since they are related to the position of the point S on the free surface (Fig. 1). which in turn is related to the accuracy with which θ is known at present. From the approximate theory the required equations are as follows:

$$\frac{1}{\sqrt{(\rho_1^2 + a^2)}} - \frac{1}{\sqrt{(\rho_1^2 + b^2)}} = \frac{1}{i} \quad \ldots \ldots \quad (3)$$

where $\rho_1 = r_1/r_0$ (see Fig. 1 for r_1) and i denotes the horizontal hydraulic gradient, averaged over the length l, in the pore-water immediately outside the drill-hole. The corresponding relation between h and i is

$$\frac{h}{r_0} = 2\pi\theta i \quad \ldots \ldots \ldots \ldots \quad (4)$$

In practical tests the value of i may often be fixed by the following consideration: When permeability tests are required to assist in the interpretation of pumping test results, it is desirable that Reynold's number should be roughly the same for both tests. This condition is nearly enough satisfied if the average hydraulic gradients at the pumped well and drill-hole are made equal.

The value of i may be estimated for a pumping test; for example for an artesian well ([6])

$$i = \frac{Q}{2\pi H k r_w}$$

For a pumped well i is likely to be within the range $5 < i < 100$, and on this assumption Table 2 has been calculated from equations (3) and (4).

TABLE 2

	$a = 6$ $b = 12$ $\theta = 0.205$		$a = 6$ $b = 24$ $\theta = 0.282$	
$\rho_1 = r_1/r_0$	i	h/r_0	i	h/r_0
1	12.3	15.7	6.5	11.5
5	19.6	25.2	11.5	20.2
10	46.0	59.0	17.0	30.0
15	101.6	130.2	37.6	66.5

Knowing the value of i required, the appropriate head h and length of drill-hole (br_0) can be found from Table 2. For $\rho_1 = 1$ the free surface point S (Fig. 1) is located at the drill-hole.

The possibility of errors in θ at the smaller heads (and hence smaller ρ_1), due to neglecting the free-surface boundary conditions in the potential solutions, was mentioned in the last section. With our present knowledge a lower limit to ρ_1 should therefore be adopted. In some of the sand-tank tests a head for which $\rho_1 = 5$ was obtained, thus justifying this value to the accuracy of these tests. It is recommended that $\rho_1 < 5$ should be avoided except when a value of $i < 11.5$ is required.

The limiting position of the free-surface at a large depth below the drill-hole is easily calculated. Let r_2 be the radial distance from the drill-hole axis to this position. Then since the vertical hydraulic gradient tends to unity for large depths, k is the limiting downward velocity and $\pi r_2^2 k = Q - Q_1$ where Q_1 denotes the discharge from the top seepage surface.

Hence
$$r_2 = \sqrt{\frac{Q - Q_1}{\pi k}} \qquad (5)$$

The value of Q_1 may be calculated from the approximate theory but it is usually small compared with Q and, in practice, the discharge Q_1 usually flows outwards over the surface and then re-enters the sandstone, in which case the total downward discharge is Q. Hence Q_1 may be neglected in estimating r_2 by equation (5).

Different vertical and horizontal permeability.

The method of permeability measurement so far described assumes that the permeability is the same in all directions, but it can easily be extended so as to determine separate values in horizontal and vertical directions. In sedimentary rocks these directions will often correspond approximately with the directions of maximum and minimum permeability. It will therefore be assumed that the permeability of the core is constant in radial directions but different from the value parallel to the axis. The method proposed is to drill identical holes, as previously described, one along the axis and the other along a radial direction in the core sample. The respective rates of inflow Q and Q' into these holes under the same head h are then observed, the core being placed with the hole vertical for each test. If $Q = Q'$ the permeability is isotropic. If however Q is not equal to Q' let k_r and k_z denote the respective permeability coefficients in the radial and axial directions. Also write $k_r/k_z = \mu^2$. Then for the drill-hole along the axis it is readily shown by the method of considering the equivalent isotropic flow in a transformed space that

$$k_r = \frac{Q\theta_\mu}{hl} \qquad (6)$$

where the function θ_μ has the same meaning as θ in equation (2), except that its value is now basied on μa and μb instead of on a and b.

For the radial drill-hole, the circular boundary of the hole becomes an ellipse in the transformed space. A new solution of the flow pattern by experimental or analytical methods is required. However, a first approximation may be obtained by using a mean radius of the elliptic hole in the solution for a circular hole. This leads to

$$k_r = \frac{\mu Q'\theta_\nu}{hl} \qquad (7)$$

$$\text{where } \nu = \frac{2}{1 + \mu}$$

From equations (6) and (7)

$$\frac{Q}{Q'} = \frac{\mu\theta_v}{\theta_\mu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

For a = 6, b = 12, the quantity on the right of equation (8) has been calculated for various values of μ. The curve relating Q/Q' with μ is shown in Fig 2, from which μ may easily be obtained for the observed inflows.

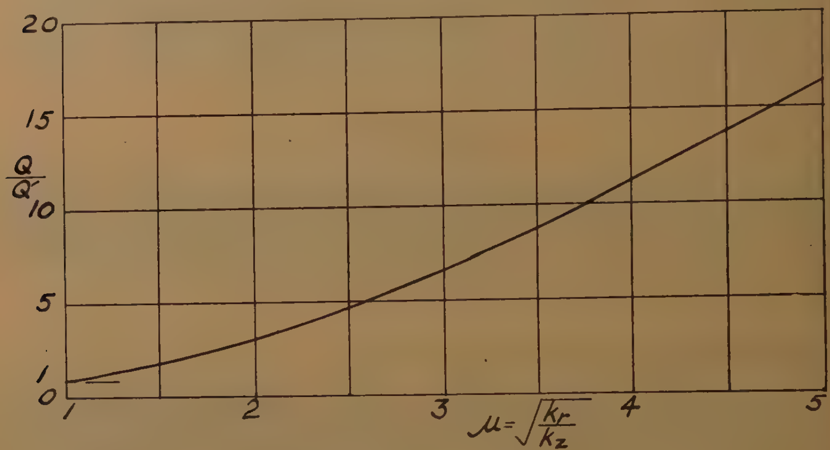


Fig. 2 — Curve for determining $\mu = \sqrt{(k_r/k_z)}$ in anisotropic case.

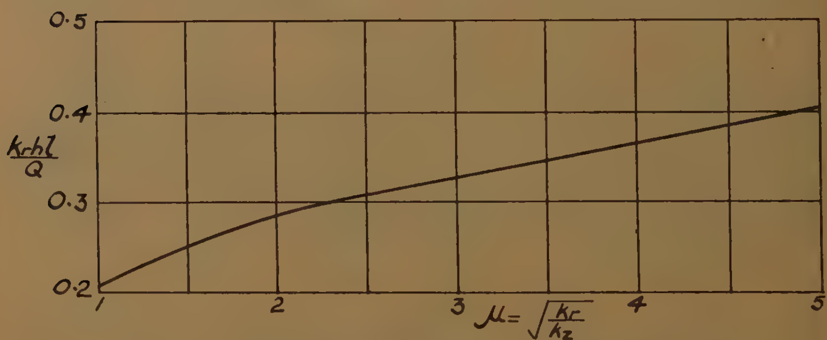


Fig. 3 — Curve for determining k_r in anisotropic case.

A curve relating μ to the dimensionless quantity $(k_r hl)/Q$, which from equation (6) equals θ_μ, is shown in Fig. 3. Hence k_r can be found. Finally $k_z = k_r/\mu^2$.

Field test and equipment

A diagram illustrating simple field apparatus which has been designed for lining the upper part of the drill-hole is shown in Fig. 4. (p. 171)

A rubber sleeve A and a metal sleeve B, each having an outside diameter slightly less than that of the drill-hole, slide on a bolt C and are supported by a flange D at its lower end. The outside diameter of the flange is equal to that of the drill-hole. A hole P is bored axially through the bolt C to enable water to enter the drill-hole. On

Photograph shows Drill-hole being formed in sandstone core with portable electric drill.

tightening the nut F, which screws on the threaded part of C, the metal sleeve pushes the rubber sleeve downwards against the flange, thus causing the rubber to swell outwards and form a watertight seal at the circumference of the drill-hole. The supporting bracket E rests on the top face of the core and ensures that the lining extends to the required depth l_1.

A flexible polythene tube G, attached to the upper end of the bolt C, is supported on a light collapsible frame and provided with a vertical graduated scale. Water is fed into the tube from a small overhead tank attached to the frame and provided with a manometer tube and outlet, controlled by a needle valve. The rate of inflow to the drill-hole is obtained by recording the rate of fall of the level in the tank, while maintaining the head constant in the tube G by adjusting the valve.

Example of permeability determination.

An example of an actual permeability test* by the method described is as follows:
Sample for test: Bunter Sandstone core, 18 inches diameter, 30 inches long.
$r_0 = 0.375$-inch, $a = 6$, $b = 12$. $l = 2.25$ inches.
For drill-hole along axis of core, $Q = 0.0378$ cu. in. per sec. h = 33 inches.
For drill-hole at right-angles to axis, $Q' = 0.0338$ cu. in. per sec. $h = 33$ inches.
From Fig. 2 for $Q/Q' = 1.112$, $\mu = 1.15$.
From Fig. 3, $(k_r hl)/Q = 0.222$. Whence, after substituting the values of h, l and Q, $k_r = 1.13 \times 10^{-4}$ inch per sec.

$$k_z = k_r/\mu^2 = 0.85 \times 10^{-4} \text{ inch per sec.}$$

Conclusion

Preliminary permeability determinations on cores obtained from the Bunter Sandstone in Nottinghamshire have shown that the proposed field technique is satisfactory.

From the measured inflow Q and head h the permeability k is easily calculated from equation (2) once the appropriate value of θ has been determined. It is believed that the recommended values of θ (Top of Table 2) are at least sufficiently accurate for testing the usefulness of the method. The accuracy of θ can be increased by further research if this proves to be desirable.

REFERENCES

(1) J. Ineson, «Darcy's Law and the Evaluation of Permeability.» Publication n° 41 de l'Association Internationale d'Hydrologie (de l'U. G. G. F.). Symposia Darcy (Dijon, 1956). p. 168.
(2) D. Kirkham, «Proposed method for field measurement of permeability of soil below the water table.» *Soil Sci. Soc. Amer. Proc.* (1945) 10, pp. 58-68.
(3) E. C. Childs, «The measurement of the hydraulic permeability of saturated soil *in situ*.» I. *Proc. Roy. Soc.* A, 215, (1952), p. 525.
(4) S. Matsuo, «A Field Determination of Permeability.» Proc. 3rd. International Conference on Soil Mechanics and Foundation Engineering, (1953) p. 268.
(5) E. C. Childs, «The measurement of the hydraulic permeability of saturated soil *in situ*.» II. *Proc. Roy. Soc.* A, 216, p. 74, (1953).
(6) M. Muskat, «The Flow of Homogeneous Fluids through Porous Media.» MacGraw Hill, p. 153.

(*) The Authors are grateful to Mr. D. Whiteley, City Water Engineer and Manager, Lincoln, for providing facilities for this test.

MOVEMENT OF UNDERGROUND WATER BELOW AND ABOVE THE PHREATIC LEVEL

P. C. LINDENBERGH
Director of Water Works, Leyden, Netherlands

ABSTRACT

1. A description is given of a test to determine the quantity of rain — and irrigation-water which can be stored in a body of dune sand with a known pore space.
2. A description is given of the experimental determination of the coefficient of permeability (k) of the Leyden dune sand.
The value of k found with the aid of the test installation agrees with formerly made hydrological calculations of k in the area.
3. Description of an «expelling test» concerning the progress of rain- and irrigation-water penetrating the sand. The test gives insight into the question of how much water a layer of sand can contain above the capillary zone when the sinking of the water is in no way hampered.
Some observations are made regarding the influence, if any, of the air pressure on the leaking out of water. Waterbalance resulting from the test and observations regarding pendular water in the finest capillaries.
4. Conclusions:
In the dune sand of the catchment area of the Leyden Water Works the vertical movement above the phreatic level of the groundwater, originating from the precipitation, takes place with a rate of infiltration of 16 cm per twenty-four hours.
The average degree of humidity of the sand above the capillary zone varies from 7-11,30% of the volume of the sand.

EFFECTIVE STORAGE OF LEYDEN DUNE SAND BELOW THE CAPILLARY ZONE

In order to determine the quantity of water which can be stored in a body of dune sand with a known pore space, a series of observations was made.

A pipe of asbestos-cement, long 4 m, ø 500 mm, was placed in a vertical position. This pipe was filled with saturated compressed dune sand from the catchment area of the Leyden Water Works (figure 1).

The sand was kept under water for a considerable time, while an upward flow of water was being maintained through the sand to expel the air from the pores. Then the flow of water was stopped and enough water was tapped for the surface of the sand to become level with the surface of the water. Next the level of the water in the sand was lowered by lowering the outlet step by step. After each lowering of the outlet the outflowing water was carefully gathered during twenty-four hours and measured.

The pore space of the sand was determined with the aid of an instrument specially designed to take samples of undisturbed soil. It appeared to be 42,75 %. The porosity of the undisturbed sand in the dunes averages 41,7 %. In practice it has to be taken into account that the wet sand will contain a small percentage of air. According to former investigations by the author the *average* percentage of air in groundwater in the Leyden dunes is 2,3. This was also checked with the aid of the above-mentioned test installation. When all the water had been tapped, water was added at the top, just as happens with irrigation, until the sand looked quite soaked again. It then appeared that 19 l water less had been absorbed by the sand than had flowed out previously. This amounted to 2,5 % of the volume of the sand, which conforms surprisingly well with the investigations of samples of wet sand as mentioned above.

By «effective storage» I understand the percentage of the volume of a body of

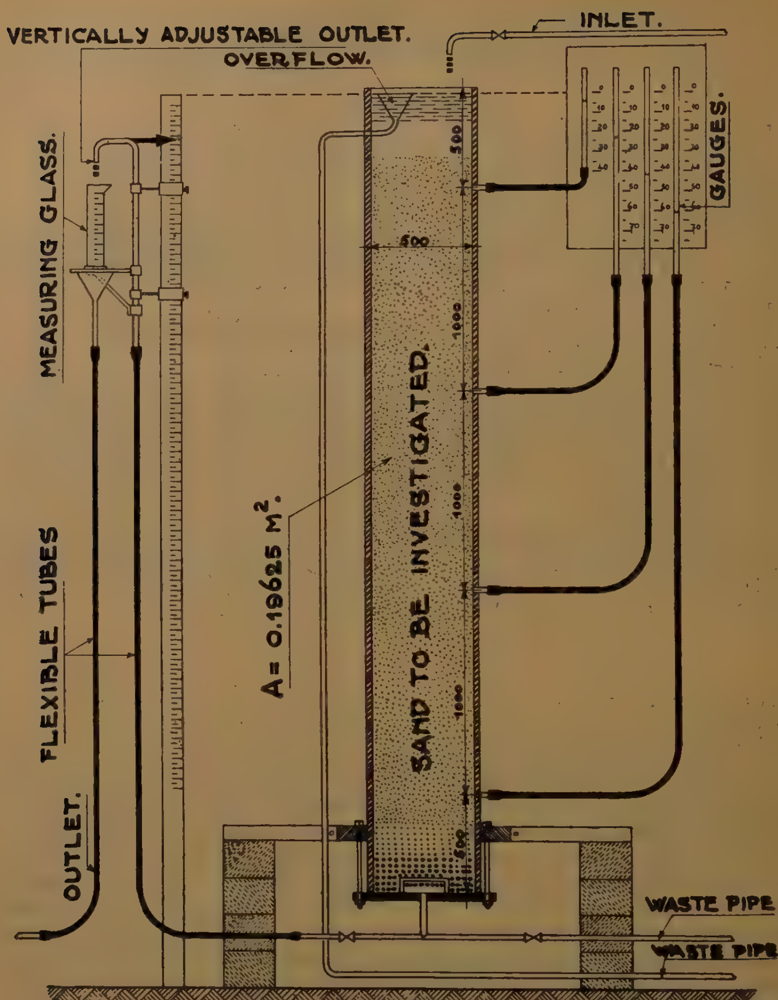


Fig. 1

soil which, under normal conditions, can be filled with as much water as may be withdrawn later on by gravity flow. The tests proved the «effective storage» of the sand to average 35,5 % of the volume of the sand. In the field this will be less, as the pore space of undisturbed Leyden dune sand is 42,75 % — 41,7 % = 1,05 % less than that of the sand in the test installation. Moreover it should also be taken into account that in the case of the test installation the air had been completely removed from the sand. According to the afore-mentioned investigations dune sand below the water still contains air to a *maximum* of 3,24 %. Considering the foregoing a mean «effective storage» of 30 % of the total volume of the sand has been accepted for the dune area of the Leyden Water Works.

Permeability of Leyden dune sand

For calculations of the movement of water in a porous medium it is essential to know the coefficient of permeability (k). For the experimental determination of k of the Leyden dune sand the same installation was used as for the determination of its effective storage. At four points, vertically 1 m apart, the pressure could be measured. By measuring the pressure at several points in the sand body the entry resistance of water into sand by a possible filter skin is obviated. The desired rate of flow is obtained by adding so much water at the top that the overflow continues to spill slightly and by placing the outlet experimentally at the height at which the desired rate is obtained. By measuring the water flowing from the outlet in a given space of time, the discharge Q is known. This test is important as it is possible to work here with different hydraulic gradients i in order to check whether the value of k remains constant with big differences of i.

During these experiments water was brought on dune sand that still contained a normal volume of air. It appeared that even with a big difference of pressure only little water flowed through the sand. The upgoing air bubbles and the air continuously escaping through the gauges initially made observations impossible. For several days, therefore, before commencing the experiment, water was made to flow downwards through the test installation. During the test, which lasted several weeks, k increased, as air was continuously carried along by the water. An average for k of 11,0 m^3/m^2 per twenty-four hours was found.

For checking purposes the actual discharges and water levels of the dune area of the Leyden Water Works during the past fourty years were used for a hydrological calculation of k in the area. In this way the average for k was found to be 11,6 m^3/m^2 per twenty-four hours, which agrees quite well with the value of k found with the aid of the test installation. This shows, therefore, that a k, determined in the above experimental way is of practical value.

Velocity of flow through the non-saturated zone

The aforesaid tests left unanswered several questions concerning the progress of the rain- and irrigation-water penetrating the sand. During the tests the air in the pores of the sand slowed down the infiltration. In order to find out how the rain- and irrigation-water behaves after infiltration into the dune sand and until it reaches the groundwater, a test of considerable duration was carried out by Dr. H. Wind Hzn. and the author under the auspices of the Central National Council for Applied Scientific Research in the Netherlands (T. N. O.).

This test was made in an asbestos-cement pipe, 4 m long, ø 80 cm, placed in a vertical position (figure 2). After the pipe had been filled with dune sand from the vicinity, the water it contained was allowed to leak out during five days.

Then we started to pour on 10 l of rainwater per day during ten days. Each watering, corresponding with a rain shower of 20 mm, was accomplished in about one minute. After a pause of eight days, during which no water was poured on, we continued the watering, this time pouring on 5 l of rainwater, representing a shower of 10 mm. This water had been tinted beforehand with fluorescence; it contained 50 mg of fluorescence per 5 l of water, a dilution therefore of 1 : 100,000. This watering with fluorescence-tinted water was continued until the colouring-matter became visible in the outleaking water; this was the case after twenty-one days. As from that moment untinted water was poured on, viz. 4,7 l per day during eleven days, followed by 5 l per day during fifty-one days. Then the fluorescence was still visible in the tapped water. Even after three months, when the installation had to be removed, the colour

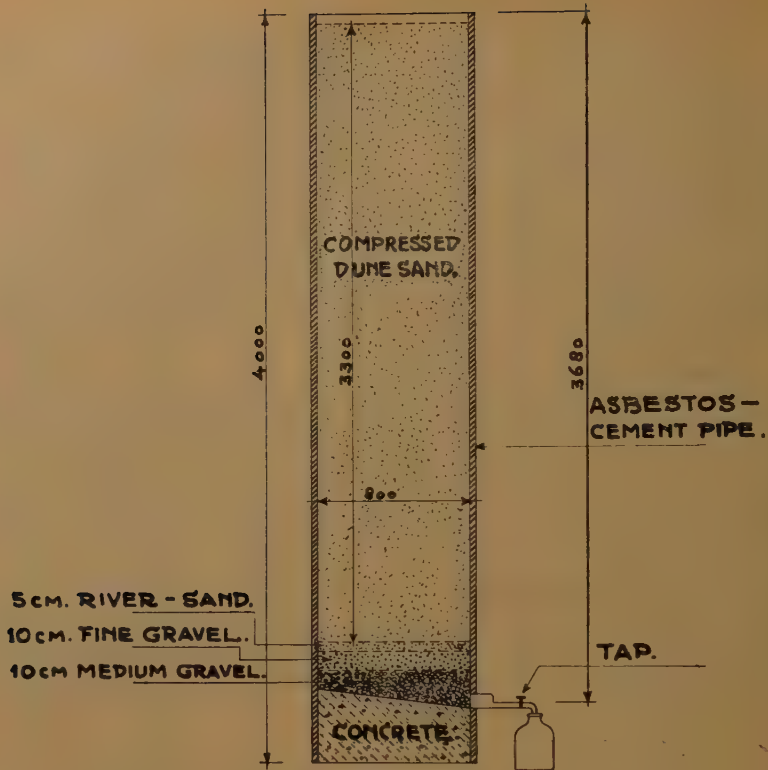


Fig. 2

had not quite disappeared. The amounts of fluorescence were then so small, however, that they could no longer be determined by the colorimeter-method employed. The sand from the installation did no longer show any discoloration.

In twenty-one days the fluorescence-tinted water sank through the sand, which means an average actual rate of infiltration of about 16 cm per day when the foundation-layers are left out of consideration, and of 17 cm per day when these layers are taken into account.

Water storage and water movement above the capillary zone

The entire water storage capacity of a soil can at most be equal to the volume of the pores of that soil. With rain or irrigation, however, the pores will hardly ever become entirely filled with water and the total water storage capacity will therefore as a rule be smaller than the volume of the pores. Part of the pores will be filled with air. The total amount of water to be stored in dune sand has already been determined by way of the first-mentioned test. The last-mentioned test, on the other hand, gives some insight into the question of how much water a several meters thick layer of sand can contain above the capillary zone when the sinking of the water is in no way hampered.

Not counting the evaporation, the maximum amount of water in the sand column during the aforecited expelling test was 11,07 % of the volume after eight daily waterings of 10 l of untinted water (equal to 20 mm of rainfall per day). When the fifty-one daily waterings of 5 l of untinted water (equal to 10 mm of rainfall per day) had ended, the amount of water in the sand column was 11,29 % of the volume, with which the maximum for this rate of watering seems nearly to have been reached. From these and some intermediate observations regarding the development of the amounts of water in the sand, it appeared that for the effectuated rate of watering the effective water storage in the 3,5 m high sand column in the pipe amounted to about 11 % of the volume.

When the sand in the pipe had been given five days time to leak out, the degree of humidity was 8,23% of the volume. After the watering had been interrupted for eight days, the degree of humidity was 7,32 % of the volume. At the end of the test, when for eighty-nine days no watering had taken place, the degree of humidity was 7,09% of the volume. It may be assumed that at this moment the gravitation water had almost completely leaked out and practically only water had stayed behind which could be held back by capillary forces. Thus field-capacity should approximately have been reached. For this soil-constant Peerlkamp states an average of 7 % of the volume in the case of Dutch dune sand. It should be noticed that the degree of humidity in the sand column was not equally divided along the entire height of the column, but *averaged* 7 % of the volume.

Influence of the air-pressure on the leaking out of water

As the daily barometer-readings at a nearby airfield were available, it was possible to check whether there exists a correlation between the above-mentioned values and those of the amounts of water daily leaking out of the pipe. The correlation was calculated during the period when daily waterings of 4,7 and 5 l respectively took place, and the humidity of the sand gradually and slowly increased from 10,41 to 11,29% of the volume. The result was — 0,070 ± 0,125. A correlation-coefficient of 1 (or — 1) indicates an absolute cohesion of the two quantities, a value 0 indicates that there is no cohesion whatever.

Taking into account the average error, it may be practically concluded from the figures found that there does not exist any correlation between the quantities at issue.

Water balance

The sand, brought into the pipe, contained		137 l of water
Poured on were	10 × 10 l =	100 l
	21 × 5 l =	105 l
	11 × 4,7 l =	52 l
	51 × 5 l =	255 l
	together	649 l
Tapped were		531 l
So that the sand should still have contained		118 l

According to the samples taken, the sand to a depth of 3,5 m contained 99-105 l of water. The missing 13-19 l will for the greater part have been present in the foundation-layers of gravel and river-sand.

Finally the following phenomenon may be pointed out.

When for the first time fluorescence was observed in the outleaking water, part of the untinted water had not yet been expelled.

At the beginning of the test the sand contained about	137 l of water
Untinted water poured on before the waterings with tinted water were started	100 l
Total of untinted water	237 l
Untinted water leaked out before tinted water appeared	175 l
Difference	62 l

When the fluorescence-tinted water started to leak out, there were still about 62 l of untinted water in the pipe. The tinted water gathered during the first days was a mixture of untinted (expelled) water and tinted (added) water, but the share of the untinted water may not be estimated at more than 5 l, so that at least 62 — 5 = 57 l, or about 3 1/2% of the volume stayed behind. This will have been present in the sand in the form of pendular water and imbibition water, that is to say for the greater part as pendular water in the finest capillaries, from which it was not expelled by the water that was poured on. This agrees with our observations of pendular water from samples of sand taken with steel tubes, long 105 cm, ø 15 cm. In those cases the water first leaking out was nearly always tinted with fluorescence as soon as the humidity-degree of the sample was 2% of the weight (= 3% of the volume) or less.

Conclusions

In the dune sand of the catchment area of the Leyden Water Works the vertical movement above the phreatic level of the groundwater, originating from the precipitation, takes place with a rate of infiltration of 16 cm per twenty-four hours.

The average degree of humidity of the sand above the capillary zone varies from 7-11,30% of the volume of the sand.

ESTIMATION OF SUBSURFACE WATER RESOURCES IN KARSTIC REGIONS

(*The rate of percolation in the Karstland*)

D. HUBERT KESSLER

ABSTRACT

The study briefly introduces to the results of those investigations which, in connection with the problem of carstic waters, were carried out in the Research Institute for Water Economy chiefly in interest of determining the resources of these waters.

The formulae and hypotheses established on the percentage of the infiltration of precipitation proved to be unreliable because, considering the measurements effectuated through decennaries, it appeared that infiltration is not linear with precipitation, but is depending, in close correlation with the development and water consumption of the plants, on the annual distribution of precipitation and may vary in the same area between 7 and 70%.

The study publishes the method with which, knowing the precipitation conditions, the infiltration per cent can be determined with satisfactory exactitude for the practice. It publishes further for a certain carstic area also the long-term average of the monthly infiltration values.

With the knowledge of the precipitation conditions we can determine for a carstic area of known extent the water recharge, resp. the permanently utilisable quantity of water. In running the wells constructed in Hungary for large-scale artificial production of carstic water it is admitted that in times with unfavourable precipitation distribution it may be—at the expense of the water quantity stored in the carst—temporaly produced more than the replenishing water quantity, taking into consideration, however, the laws of the subterranean hydraulic balance. According to computations made for hungarian conditions the long-term mean recharge in carstic area is 6-11 l/sec per km^2.

The study reports also the results of the experiments connected with infiltration velocity as well as the variations resulting from natural and artificial influences of the carstic water levels, observed through borings.

It gives account at last of those practical preparatory works which are to be done for determining the water resources of a carstic area.

Increasing industrialization in the whole world, construction of new towns, endeavours of the raising of living standards set always new problems for the research workers and the projectors also in the range of water supply for industrial and consumptive use.

Natural conditions do not permit any more in many areas to put new water supplies in the service of manhood by the conventional methods of water procuring; it is therefore unavoidable in such areas to apply new methods and open new vistas.

Such necessities occured also in Hungary where the raw materials for industrialization are to be found partly in dolomitic or calcareous karstic regions. Such regions —as incorporations of water scarcity—are generally passed over in planning developments. Nevertheless in Hungary the question was raised alternatively: either the industrial plants will be located in a region with more favourable water-supply conditions and raw material transported there, or the water must be conducted by expensive pipelines to the consumers sited in karstic regions.

Following the thorough consideration of the particular geo-hydrological conditions in Hungary and of the economical points of view a third solution of the problem was attempted: the artificial development (tapping) of water supplies on the site. The first attempts were begun with in 1949 with so a great initial success, that they

raised in many circles exaggerated expectations, which later were not fulfilled in every case so that ultimately many opponents of artificial development of karstic waters came forward.

The course of scientific investigations pursued later on for several years, based on practical data and experience, enabled the experts to determine where, when and in which extent it is possible to rely on the artificial development of karstic waters in a safe and reasonable way.

One of these artificial methods of karstic water development was to drive down a borehole into the water-conducting channelways in the karstic rocks presumable on the base of geological observation, and to lift the water by submersible pumps. The sinking of such boreholes has sometimes missed its target due to the restricted width of these water-conducting channels and fissures. There were sunk therefore vertical shafts surpassing the depth of hundred meters enabling to descend below the table of the karstic water, and, by means of horizontal galleries driven, the water bearing caverns and fissures were searched for. This method was successful in every case and nowadays many important industrial plants and residential settlements and, moreover entire towns are supplied by karstic water developed in this way.

These shafts extracting karstic water functioned for some years perfectly well which fact seemed to confirm the views maintained about the inexhaustibleness of karstic water. However, after some years the water yield of one or another shaft decreased, because the withdrawal exceeded the natural replacement of water reserves; on this account the natural karstic water table (nappe) has declined also. The shafts had to be sunk deeper and the pumping equipment had to be installed on a lower level. These experiences brought into prominence the *question* of the replacement of karstic water supplies and *of the continuous exploitation of the water resources.*

Although most of the experts consider the karstic water to be of meteoric origin there are many of them who believe the karstic water of higher temperature as juvenile (connate) and infer that its quantity can not be judged. Even if we suppose that karstic water comes entirely from precipitation, there remains the open question of the rate of replacement and of the rate of percolation (infiltration). A fairly large measure of uncertainty reigned in this respect; in the technical literature we generally meet with evaluations between 20 and 40 per cent, but even these are without practical support.

The study of the replacement of water supplies and of the water resources permanently available (perennial safe yield) became in Hungary a practical and important problem of the national economy, so that the Research Institute for Water Resources started systematical investigations for its elucidation.

In the greater adjacent karstic regions boreholes for water table observations, standard areas for observations were set up, as well as experiments were performed for the study of the conditions of karstic water infiltration. Further systematic observations and recordings of every important spring and in first line of karstic springs, were organized.

The relationship between the yield of springs and the precipitation has been estimated generally by employing the traditional *Maillot*-formula:

$$Q = n\,H\,F,$$

where «Q» is equal to the yearly yield of the spring, «n» a factor depending on the surface of the ground, «H» the annual amount of rainfall and «F» the area of the watershed. Following this opinion the yield volume of the springs or rather the percolated water-volume feeding the springs is in linear proportion to the annual precipitation.

Supported by many thousand results of measurements collected for long years, it was conclusively established that the yearly yields *do not always follow the annual rainfall*, and moreover in some cases just the contrary of it was ascertained: under

conditions of less rainfall the yield, i.e. percolated water feeding the spring, increased to its tenfold, and in a year with proportionately high precipitation, abundant karstic springs dried up.

As the positive data of practical measurements did not confirm the opinion concerning the existence of a constant rate of percolation, a method had to be found by means of which the volume of the percolated water (infiltration) could be determined with an exactness sufficient for practical purposes.

Investigating the closer connections of rainfall conditions and spring yields one had to rely in first line upon the regularities which presented themselves at the examinations of the springs in the most conspicuous manner. Such a fact is the *critical influence of the winter and early-spring precipitation upon the spring yields*, further the experience that relatively small water quantities of rainfalls increased the yields quite strikingly if the ground was previously considerably soaked.

The greater influence of the precipitation in the beginning of the year is due undoubtedly to the increased water consumption by the surface vegetation, in first line by the forests, which is confined to a particular period of the year. The precipitation in the summer months is scarcely reflected by the water yield of the springs.

An example: the annual water consumption of a beech forest amounts to 492 mm, when the annual precipitation comes to 800 mm. This intensive water consumption is limited mostly to the period between the end of April and the beginning of September. This statement is verified also by the great differences between the ground water levels measured in forested and cleared areas. Not only the forest consumes much water but the grassy area too. *Wollny* states that the water consumption by a grassy area amounts to 300 mm during the three and a half summer months. Potatoes consume 42 mm from the 46 mm rainfall in May.

The otherwise well known great water consumption by the vegetation given above in broad outlines, exerts its influence also on the water economy of nature; it can not be indifferent therefore how the annual precipitation is distributed seasonally.

It must be investigated further how the circumstances of infiltration are developing after the defoliation and the ceasing of the sap circulation.

The channelways of karstic springs are generally not cavernous and of greater dimensions only in a greater depth below the surface. The predominant part of the meteoric waters can descend into these wide channels, connected with the springs, exclusively through narrow capillaries. After a summer draught an important part of the rainfall never gets down into the deeper lying rills of the springs. Instead it remains under the influence of the capillarity forces as pellicular and film water in the narrow capillary system which has an extraordinary great capacity. The increased activity of the springs can start but after the complete saturation of the capillary system. This is proven by the observation of the fact that after a longer rainy period a relatively small precipitation increases rapidly the yields of the springs. Concerning this we have made tests in several caves and controlled the rate of water-trickling with measuring vessels in correlation to the precipitation.

It can be stated that the autumn precipitation prepares in a certain way the conditions for the development of infiltration in the first part of the next year.

* * *

For practical investigations in a typical karstland of Hungary, in the Mecsek-Mountains, the 22 years measurement data of the Tettye-spring, (a tubular spring) abounding in water were at disposal. The yield of the spring, as it serves the water supply of the city of Pécs, is measured daily. In the center of the exactly circumscribed watershed a rainfall record station is in operation for several decades of years. The

topography of the ground—at an average height of 500 meters—shows typical features of the karstification. About 75% of the surface is covered by beech wood.

The annual data of the yield of this spring do not show close correlation with the annual precipitation; in many cases just the contrary of it has been observed. It was most conspicuous that in 1947 from the precipitation of 524 mm 67% appeared in the yield of this spring, whereas from the rainfall of 534 mm in 1949 not more than 7%. The rate of infiltration varied consequently in the same area up to its tenfold. In other years similar, though not so striking contrasts could have been stated.

Now if we examine the seasonal distribution of the precipitation in the above mentioned example, it becomes evident that in the year of 1947, 269 mm of precipitation, i.e. 52% of the total annual rate — were falling in the first four months of the year, conversely in 1949 not more than 64 mm, i.e. 11,5% of the total annual quantity fell in the months determinative for the percolation (infiltration). The same relation was found between data concerning the interrelation of precipitation and the yields of the spring also in other years, proving unequivocally that *the relation of the precipitation of the first four months to that of the total year is determinative for the percolation feeding the spring.* Therefore this relation, expressed in percentage, is termed *determinative precipitation rate.* (μ).

If we evaluate for every single year of the recorded 22 years the determinative precipitation rates on the basis of the annual and seasonal data, and plot them to one axis of a diagram against the other axis showing the rates of percolation determined on the base of measured yields of the spring, we obtain points which form an approximately continuous curve, yet we find some protruding values. Now when examining closely the years showing such greater deviations, it is found that the conditions of precipitation in the four last months of the years preceding the years at issue, varied considerably from the perennial average. Consequently the conditions of precipitation in the preceding year influence the circumstances of percolation also, the reasons for which were given above.

Accordingly, the determinative precipitation rate must still be corrected by a constant value («*k*») depending from the conditions of precipitation in the last four months of the previous year.

This constant «*k*» can be obtained by determining the rate of the difference between the precipitation of the last four months of the preceding year and the perennial average precipitation of these four months to the perennial average precipitation of the same four months. The positive or negative sign must be considered also. The value obtained is termed the corrective percentage of precipitation ($\varkappa$).

The relation of the corrective precipitation rate to the correcting constant is shown by the following empirical table:

Corrective precipitation rate ($\varkappa$)	Values of correcting constant (k)
0 - 5	0
6 - 15	1
16 - 25	2
26 - 35	3
36 - 45	4
46 - 55	5
56 - 60	7
61 - 65	10
66 - 70	13
71 <	15

It goes without saying that the sign of the corrective percentage applies also to the correcting percent.

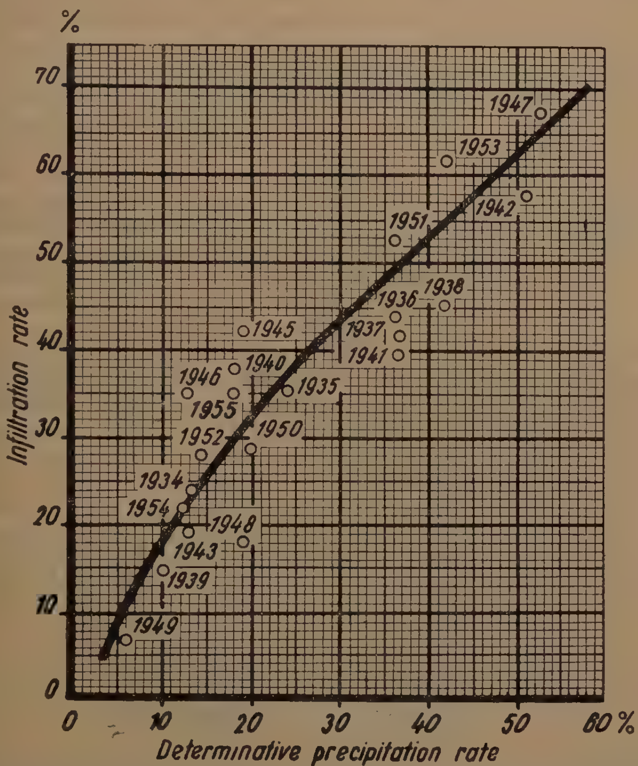


Fig. 1 — Percolation curve plotted on the basis of recorded data of 22 years, enabling the reading off of the percolation rate if the conditions of precipitation are known.

Figure 1 indicates on the abscissa the corrected determinative precipitation rates estimated on the basis of the precipitation data of the Tettye-spring watershed, plotted against the percolation rates determined on the basis of the measured yields of the spring on the ordinate. Aided by the points obtained in this way a graph was drawn, the curve of percolation (infiltration), from which the percolation rate can be read off if the conditions of precipitation are known.

The serviceableness of the graph has also been demonstrated in the Hungarian mountains of medium height, up to elevations of 900 meters, in other well circumscribable and controllable karstic regions. Moreover an opportunity presented itself to explain the apparent contradictions in the yield data of springs and the circumstances of precipitation in the Rax and Schneeberg area (Austrian Alps) by the help of the curve of percolation (infiltration). In higher mountains with a shorter period of vegetation, the graph appears shifted upwards i.e. the percentage (rate) of percolation, admitting the same determinative precipitation rate, will be higher than in the Hungarian mountains of medium height. It would be most desirable to control and

extend by special measurements the method employed in Hungary also in other karstic regions.

The data of individual years, e.g. of 1940, may differ sensibly from the diagram-values. This is due to the fact that in this year the months of April and May were colder than the average and vegetation developed but later, therefore infiltration was greater. By consideration of such temperature coefficients the method would be more accurate but this would render its practical employment rather too difficult.

It can be concluded from the statements above without doubt that *the rate (percentage) of percolation (infiltration) is not a constant value but may vary even in reference to the same area between wide ranges: 7 and 70%*. Its value is influenced by the annual (seasonal) distribution of the precipitation, in first line by the relation of the precipitation in the first four months to the precipitation of the total year. The amount of the rate of infiltration can be determined in knowledge of the precipitation data, by reading of the diagram explained above, with the exactness fulfilling practical needs.

* * *

Relying upon the measurement data of 22 years available in the following table there are disclosed the perennial average percolation (infiltration) rates of each month. The same are plotted also in a graph. (See figure 2).

January	50,2%
February	73,3%
March	123,6%
April	65,4%
May	47,2%
June	28,7%
July	20,6%
August	18,1%
September	15,6%
October	12,3%
November	24,3%
December	51,3%

Fig. 2 — Perennial average monthly percolation percentage in the 12 months of the year plotted on the basis of recorded data of 22 years.

It is to be noted that the value in March surpassing 100% is due to the melting of the snow which constitutes an accumulated precipitation.

Similar results were brought about on the other hand by our experiments performed with artificial floodings above caverns and underground measurements of the rate of trickling.

It may be emphasized that the slopes of the ground surface play no important role in the process of percolation, as on occasion of our experiments the karstic ground surface of different slopes *absorbed any quantity of precipitation, practically without runoff taking place on the surface.*

* * *

A preliminary condition of being able to estimate the stored quantity of karstic water is the determination of the percolation rate, expounded above. Besides we must know exactly, relying upon the findings of detailed geological survey, the extension of the karstic watershed. When estimating the stored supply of karstic water in Hungary we have considered the Mesozoic limestone and dolomitic formations, further the fairly karstified limestone ground forms of the Eocene. It may occur that a non-karstic formation adjacent to the karstic area but having a more elevated surface transmits its surface runoff water upon the karstic area. In such cases the non-karstic surface is to be considered also.

The estimation of the subsurface karstic water resources of Hungary was performed for the total territory in question on the basis of the principles above. The result corresponded with an exactitude of 18% with the sum of the effectively extracted water quantity and of the natural yield of the springs. Under areas where the estimations show that replacement is less than the effectively exploited and running-off karstic water, the karstic water table is declining substantially, which phenomenon points to the loss of equilibrium in the natural ground water economy.

As results of the estimations of karstic water resources in Hungary we obtained for the natural replacement of supplies (replenishment) values of 5,6-10,9 litres/sec per square kilometer — depending from the rainfall rate and the elevation above sea level of the territory in question. These values relate to the perennial average rainfall. The artificial development (tapping) of the karstic waters has the advantage that purely the perennial average water replacement must be considered and the variations appearing in the particular years can be balanced with the water resources stored in the deep-karst — by means of shafts sunk into suitable depths. It is understood that this can not be admitted but for a transitory period, because if more water is steadily withdrawn than the safe amount warranted by replacement, the karstic water table will be lowered permanently which feature would necessitate the deepening of the development shafts themselves. As a matter of course the deeper is sunk the equipment serving for developing the water the greater will be the catchment area belonging to the shaft and we will be able to utilize the water stored in the karstland in a greater extent for balancing the differences of meteoric supply.

According to perennial observations in the experimental regions of karstic hydrology, dolomitic karst can store water better than calcareous karst. Dolomite has a finer void system and does not conduct the precipitation so promptly to the springs as the wider cavernous gangways of the limestone do. Therefore in the dolomite the precipitation produces much higher bosses (humps) in the karstic water table. The survey of ground water contours has shown that the fluctuations between water table levels can exceed 6 meters. Relying upon experiments carried out in karstic areas velocities of percolation in the range of 3,9-8,2 m/hour were observed.

Summarizing the above, *the water resources of a karstic region can be estimated by determining, following the method disclosed above on the basis of the perennial*

precipitation data, the valid perennial average percentage (rate) of percolation. With full knowledge of this we are able to determine the height of the water column, which percolates as a perennial average into the karst — usable for water development. On the basis of geological surveying and knowing the extension of the karstic catchment area, we can determine the annual water quantity safely withdrawable from the territory concerned.

It must be insisted on that the percolation curve plotted for the determination of the percolation rate (percentage) is valid for the Hungarian mountains of medium height, up to an elevation of 900 meters above the sea level. *It would be most beneficial to control it, and extend its validity range by international cooperation also for other, more elevated regions.*

THE USE OF FILTERS TO MAINTAIN HIGH INFILTRATION RATES IN AQUIFERS FOR GROUND WATER RECHARGE (*)

LEONARD SCHIFF (**)

ABSTRACT

A method of recharging ground water is the injection of water into aquifer material through pits, trenches, shafts, and wells. Grit, sand, and aquifer-sand filters doubled and more than doubled the total infiltration into aquifer material over a 70-day period at Bakersfield, California, U.S.A. Decreases in infiltration rate are associated with increases in suspended load in the water supply. Increases in infiltration rate are attributed to decreases in viscosity and increases in total salts in the water supply. Losses in hydraulic head in the filter material and in the aquifer material are presented.

INTRODUCTION

A method of recharging ground water is the injection of water into aquifers through pits, trenches, shafts, and wells. Pores in the aquifer material clog with time. A major cause of clogging is the suspended solids carried by the water. Much of the clogging may take place at or near the surface of the aquifer material. The depth of sedimentation in the aquifer depends largely upon the size of particles in the suspended load and in the aquifer material, flow characteristics and other characteristics of the water and soil. This paper deals largely with an experiment to find filter materials that may be placed over aquifer material to maintain high infiltration rates over a period of time.

PREVIOUS WORK

SCHIFF and JOHNSON (1957) described initial tests with filters overlying aquifer material in infiltrometers. A sand filter doubled the total infiltration into sand aquifers over a period of a few months at Bakersfield, California, U. S. A. Particle sizes of the filter sand ranged from 0.5 to 2.0 mm. Peagravel filters 1/8 and 1/4 inch in diameter had little effect, partly because 81% of the material carried in suspension by the infiltrating water was clay. Sedimentation occurred in the aquifer material rather than in the pea-gravel filters.

SUTER (1956) has shown that, at the 1/7-acre Peoria Pit in Illinois, U. S. A., injection rates increased from an average daily volume of 3.2 to 9.5 acre feet/day when the sand filter over the aquifer was replaced with 1/4 inch pea gravel. Considerable sedimentation occurred at or near the surface of the filter. The filter has been effectively cleaned by suction.

SCHIFF (1956) has shown that, at the 1/10-acre pit at Bakersfield, California, U. S. A., with 1/29-acre of sand exposed 1/4 inch pea gravel was not effective in increasing or maintaining higher infiltration rates. The injection rate declined from

(*) Presented at the 11th General Assembly of IUGG, Toronto, Canada, September, 3-14, 1957.

(**) Hydraulic Engineer, Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Bakersfield, California.

a daily volume of 2 to 1.2 acre feet/day in 82 days. Clogging deposits occurred in a thin plane on the sand aquifer benath the filter on both the bottom and sides of the pit. These clogging deposits were removed by scraping with flat-nosed hand shovels to restore the infiltration rate.

The initial tests at Bakersfield indicated that filter materials are desired that will cause sedimentation through a depth of the filter and thus retain sufficient porosity to sustain reasonably high infiltration rates during a spreading season. The depth of sedimentation should be such as to permit cleaning by suction or by scraping at a reasonable cost.

Procedure

Figure 1 shows 16 manometer-equipped infiltrometers with supply tanks located in a pit exposing aquifer material similar to the material found in the 1/10-acre pit at Bakersfield. The infiltrometers are three feet long and one foot in diameter. They were driven one foot into the aquifer material. Each infiltrometer is supplied with water from a storage drum. A float-controlled valve in each infiltrometer maintains a constant surface head of water within the infiltrometer. Infiltration rate in a given infiltrometer is obtained by shutting off the water supply to the drum and measuring the rate of change of volume of water within the drum. The supply to the drum is turned on before the drum runs dry, thus maintaining the constant head of water within the infiltrometer.

Washed and dried filter materials 0.2 foot in depth were placed over the aquifer material. These materials included sand ranging in size from 0.5 to 2.0 mm, aquifer material ranging in size from 0.5 to 5 mm (screened to eliminate all particles less than 0.5 mm), and «turkey grits» or sharp angular gravel ranging in size from 0.5 to 5 mm. Hereinafter the screened aquifer material is referred to as the aquifer-sand filter. Four infiltrometers containing aquifer material had no filters and are referred to as the controls. All filtering materials and controls were replicated four times in a latin square design. Tables 1 and 2 show particle size analysis for the aquifer material and filter materials, respectively.

The experiment started February 12, 1957. Kern River water was used exclusively until near the end of February when pumped ground water was added to the river water to maintain a sufficient supply for irrigation. Computations shown herein covered the first 70 days of the experiment. A surface head of 1.9 feet was maintained on the surface of the aquifer material during the entire run. Losses in hydraulic head at the bottom of each filter and 0.1, 0.2, and 0.4 foot beneath the surface of the aquifer material were determined with manometers, Figure 2.

Results and Discussion

Table 3 shows the maximum, minimum, 70th day, and average daily infiltration rates for the aquifer material overlain by the various filter materials. Variance due to location of infiltrometers is similar and non-significant. Increases in infiltration rate with the grit, sand, and aquifer-sand filters compared to the aquifer material alone are significant at the 3%, 1%, and 1% levels, respectively. The aquifer-sand filter was the most effective. About 25% of original aquifer material was removed by screening to form the aquifer-sand filter. The sand filter gave infiltration rates only slightly less than the aquifer-sand filter. The sand filter was composed of particle sizes ranging from .5 to 2 mm, whereas 81% of the aquifer-sand filter was composed of this range with the remainder between 2 and 5 mm.

Figure 3 shows hydraulic head losses occuring in the filters, suspended solids, total salts, percent sodium in the water supply, and the temperature of the water for a 70-day period. All measurements were made within the infiltrometers. Temperatures were about the same in all infiltrometers at any given time. Figure 4 shows the daily average infiltration rate for aquifer material alone and with various filters. There is a rather sharp decline in the daily infiltration rate on the tenth day when an appreciable increase in suspended solids in the water supply occurred.

The unprotected aquifer material tends to cause sedimentation in a thin plane at its surface. This clogging in a thin plane on the surface of the aquifer material was also observed on the 1/10-acre pit at Bakersfield when unprotected or covered by 1/4-inch pea gravel. Particle sizes less than 0.5 mm in the aquifer material appear to be a major factor in causing sedimentation and in retarding infiltration rates. The grit filter did not appear to be appreciably helpful in preventing suspended material from reaching the surface of the aquifer material as indicated by the rapid initial drop in rate of infiltration. Also, hydraulic head losses were small in the grit filter as compared to the sand and aquifer-sand filters, Figure 3.

The rather abrupt drop in daily infiltration rates from the 20th to the 30th day in the infiltrometers containing the sand and sand-aquifer filters is consistent with the large increase in hydraulic head losses occurring in these filters. Presumably, appreciable clogging is beginning to take place in these filters with the accumulation of suspended solids. Temperatures are not sufficiently different on the days involved to be significant.

Important increases occurred in the daily infiltration rates after the 35th day in all infiltrometers containing filters as compared to small increase in rate for the aquifer material with no filter. About this time and subsequently, hydraulic head losses remained somewhat constant and even declined. Although the amount of suspended solids in the water supply remained fairly constant from the 35th to the 55th day, accumulations of solids would continue and offer no explanation for the increase in infiltration rates or decline in hydraulic head losses. The percent of sodium in the supply water rose only slightly during the experiment. The adverse effect of sodium would not be appreciable at such low total salt concentrations. Well water alone contains about 370 ppm total salts and a sodium percentage of 27.

After the 35th day, two major factors appear responsible for increases in infiltration rates. Temperature increases and resultant reductions in the viscosity of the water undoubtedly accounted for most of the increases in infiltration rate. The increase in infiltration rates in the aquifer material alone and under sand and aquifer-sand filters are consistent with the decreases in viscosity. However, the large increases in infiltration rate in the aquifer material under the grit filter can only be partially explained by decreases in viscosity. Due to the increase in salt content of the water after the 25th day, it is possible that flocculation of fines took place more readily in the grits and in the aquifer material immediately beneath the grits than in and under the other filters. About 81% of the suspended load is clay.

Flocculation is an important consideration that warrants further experiments along such lines. If filters could be made more effective by occasional flocculation of the fines by «shot» or «slug» treatments with materials as ferric sulfate or calcium chloride, such treatments may be economically justified. The grit material, as do all filters, tends to become more effective as a filter with time. However, a filter is considered effective in this experiment when it distributes fines through a depth rather than on a plane and thus maintains sufficient porosity for a high infiltration rate.

Another factor which warrants further consideration is the effect of temperatures on the expansion of gas within the aquifer material and filters. The expansion of gas may disrupt deposits on the aquifer material and in the filter more readily on and immediately under the grits than in and under the other filtering materials. Movement

of the disrupted clays could occur in various directions and thus increase the porosity and the infiltration rate. Such disruption may ultimately facilitate flocculation of fines.

Figure 5 shows the hydraulic head on the surface of the aquifer material beneath each filter. The maximum hydraulic head on the aquifer material was two feet where no filters were used and slightly less than two feet under the grit filters throughout the 70-day period. Hydraulic head losses in 0-0.1 foot of aquifer material beneath various filters are also shown. The maximum hydraulic head of two feet was lost in the 0-0.1 foot depth of aquifer material within 22 days when no filter was used or when grits were used. The high increase in suspended load on the 10th and 11th days, Figure 3, is reflected in the decrease in infiltration rates, Figure 4, and in the increase in hydraulic head losses on the 11th day, Figure 5.

Hydraulic heads of 1.17 feet and 0.45 foot were lost in the aquifer material from 0-0.1 foot at the 70th day under the sand filter and aquifer-sand filter, respectively. The data indicate more rapid clogging of the aquifer material in the following order: grits and no filter (quite similar), sand filter, and aquifer-sand filter.

Conclusions

By the use of filters, the rate of water entry into aquifer material was sustained at approximately double that of aquifer material with no filters. Hydraulic heads greater than atmospheric were maintained at the 0.1 foot depth in the underlying aquifer material throughout the 70-day period by the sand filter and aquifer-sand filter. These measurements thus indicated that less sedimentation took place in the aquifer material where filters were used.

Although the average 70-day infiltration rate for the grit filter was lower than the sand and aquifer-sand filters, the infiltration rate at the 70th day for the grit filter was about double that of the other two in spite of the early deposit of fines on the aquifer material beneath the grits. Thus from the standpoint of infiltration rate, the grit filter became more effective with time. Hydraulic head losses and viscosity changes within the grit filter do not account for all of the increase in infiltration rate. Viscosity changes could account for the increases in infiltration rate in the sand and aquifer-sand filters. Apparently other actions, such as flocculation within and immediately under the grits or the disruption of deposits and consequent increase in porosity by gases, affected the infiltration rate.

Filters can be justified if they maintain the infiltration rate of aquifer materials sufficiently high to offset the cost of their use plus maintenance by suction, scraping or replacement.

Acknowledgments

Grateful acknowledgment is made to Curtis E. Johnson for making some of the laboratory determinations and for suggestions, to Eldred S. Bliss for suggestions, and to Herschel K. Kimble for assitance in maintaining the filter experiment, collecting data, and making calculations.

The writer appreciates the land and water made available for the experiment by the Kern County Land Company.

REFERENCES

Schiff, Leonard, and C. E. Johnson, Some methods of alleviating surface clogging in water spreading with emphasis on filters. Presented at the AGU meeting, February 15, 1957, Sacramento, California; in press.

Suter, Max, High rate recharge of ground water by infiltration, Circ. No. 54, Dept. Registration and Education, State of Illinois, 1956.

Schiff, Leonard, The Darcy Law in the selection of water spreading systems for ground-water recharge, Publ. No. 41 of the Intl. Assoc. of Hydrology, IUGG, Vol. II, pp. 99-110, Darcy Symposia, September 1956, Dijon, France.

DETERMINATION OF PERMEABILITY BY PUMPING FROM A SPHERICAL WELL

T. ONODERA
Public Works Research Institute, Ministry of Construction, Japan

Abstract

A spherical metal crust was so designed as to be used as a test well to determine the coefficient of permeability of an aquifer. The values of coefficient of permeability were referred to those values determined from the amount of water level depression after a long period of pumping in the observation wells arranged in a cross in measured distances. Thus the error, due to the disturbance of aquifer adjacent to the spherical well caused by digging and filling back to set the sphere, was found unnecessary to be taken account. And the permeability can be determined with sufficient accuracy by pumping from the spherical well alone.

As the author's spherical method is more simple and theoretically more accurate than other methods of determining the coefficient of permeability, permeability may more easily and accurately be determined in many places throughout the aquifer.

Introduction

Various methods have been attempted to determine the permeability of aquifer and a number of important techniques have been developed. However some of them stand theoretically on approximation and some others, though theoretically appropriate, require laborious field procedures.

Owing to their sedimentaly properties most aquifers have vertically and horizontally heterogeneous structure of so to speak an overlapping of false bedding in large or small scale. Accordingly permeability differs from place to place and when the permeability of narrow area is concerned, this difference comes into question. And permeabilities should be determined on as many points as possible in the aquifer both horizontally and vertically, and for this purpose a technique is needed to perform the permeability determination test more easily than other procedures. The author has introduced the idea of spherical well which is the most simple configuration and thereby theoretically most adequately be treated to the permeability determination.

Theory

From the point of view of potential theory all aspect of groundwater motion can be treated similarly to the theory of electricity, magnetism or heat conduction, and among which electrical analog is known to be most helpful to the study of groundwater motion.

For convenience, let us consider the case in which a spherical well is set in an isotropic homogeneous aquifer extending widely in horizontal and vertical direction. When groundwater is pumped from the spherical well through a very slender pipe, the condition is just the same as determining the conductivity by measuring the potential on the surface above the spherical electrode in a semi-infinite isotropic medium.

Laying the detailed derivation on the potential theory, the coefficient of permeability is given by

$$k = \frac{Q}{2\pi t d_0} \tag{1}$$

where k: coefficient of permeability
t: depth of well from the groundwater table before pumping
q: discharge from the well
d_0: draw down.

Equation (1) is valid in the semi-infinite aquifer and the conditions $t > r$ and the depth of the aquifer $\gg t$ are fulfilled. But in actual cases all aquifers have finite extension, i.e. they have definite depth and width, and have always some surface water from which the groundwater is supplied. So eq. (1) must be modified to fit each field condition, or d_0 should be kept within so small a quantity that the practical aquifer might be regarded to be very extensive.

Design of the Sphere

The sphere to be used as a well was designed as shown in Fig. 1. It is made of bronze 5 mm thick and is composed of two semi-spheres detachable by means of screws. The outer radius is 15.9 cm which approximates 100 when multiplied by 2π (afterwards it was found unnecessary). They have quarter-foil holes each on each face of hexakis octahedron, diameter of each foil being 20 mm. As the holes are too large for sandy aquifer, they are covered with detachable screens from inside, of which openings are also quarter-foiled and may be fitted to the grain-size of quifer materials.

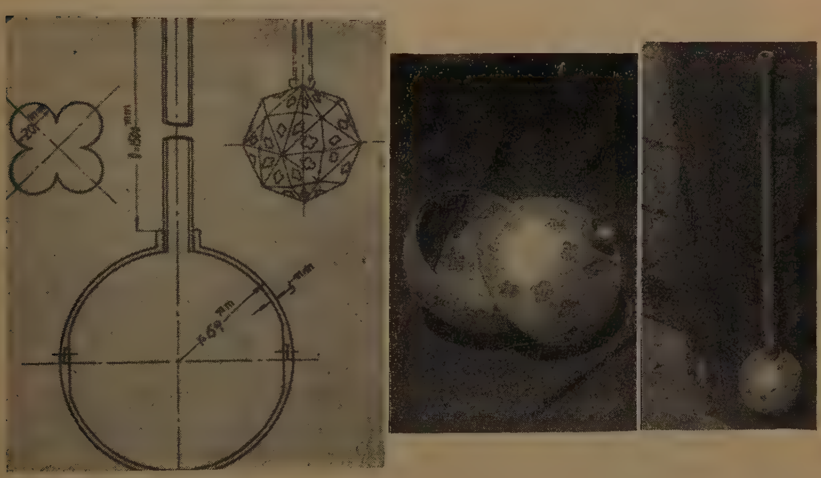


Fig. 1 — Spherical Well

To the top of the sphere an iron pipe (1/2″ dia.) 1.5m long is screwed through which the ground-water is pumped. The larger the sphere is the better may be the result obtained, but inevitably the test execution becomes more laborious. A sphere with dimension chosen here can be set in a 14″ bore hole in the case where the ground-water table is deep below the ground surface or pumping is desired in a particular deep layer. A foot-valve may be inserted in the sphere when needed.

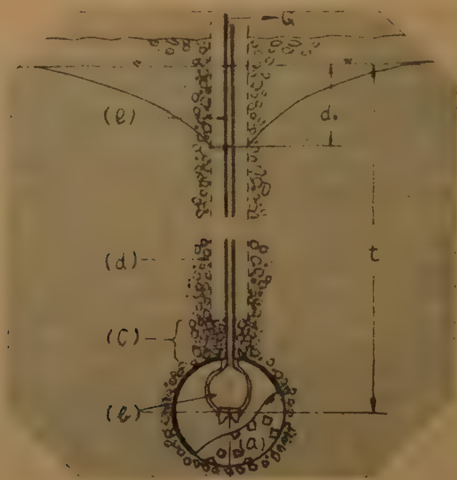


Fig. 2 — Setting of Spherical Well

Setting of the Sphere (Fig. 2)

The place where the permeability is to be determined is excavated to the required depth with as much care as possible not to disturb the packing condition roud about. Then the sphere (*a*), connected with suction pipe (*e*) with necessary length and attached with foot-valve (*b*) when needed, is placed and filled back in a suitable measured depth (*c*). The part (*c*) is better to be filled as much deeper as possible within the range not to cause draw-down sink below the bottom of observation well guarded by a punched metal cylinder (*d*). Of course it is desirable to fill back the excavated material to the original state of packing, but it is impossible and as the error, caused by the disturbance due to excavation and filling back, is found negligible as stated later, no slender care is needed.

Pumping Test

By assuming a proper value for k, the capacity of the pump, amount of Q and the type of measuring Q to be used are easily foreknown by the chart shown in Fig. 3, which shows relationship between k and Q with assumed d_0 and t calculated from (1). Though the chart is to foreknow the test dimensions to plan the test, it may be utilized to know the rough value of k from test dimensions.

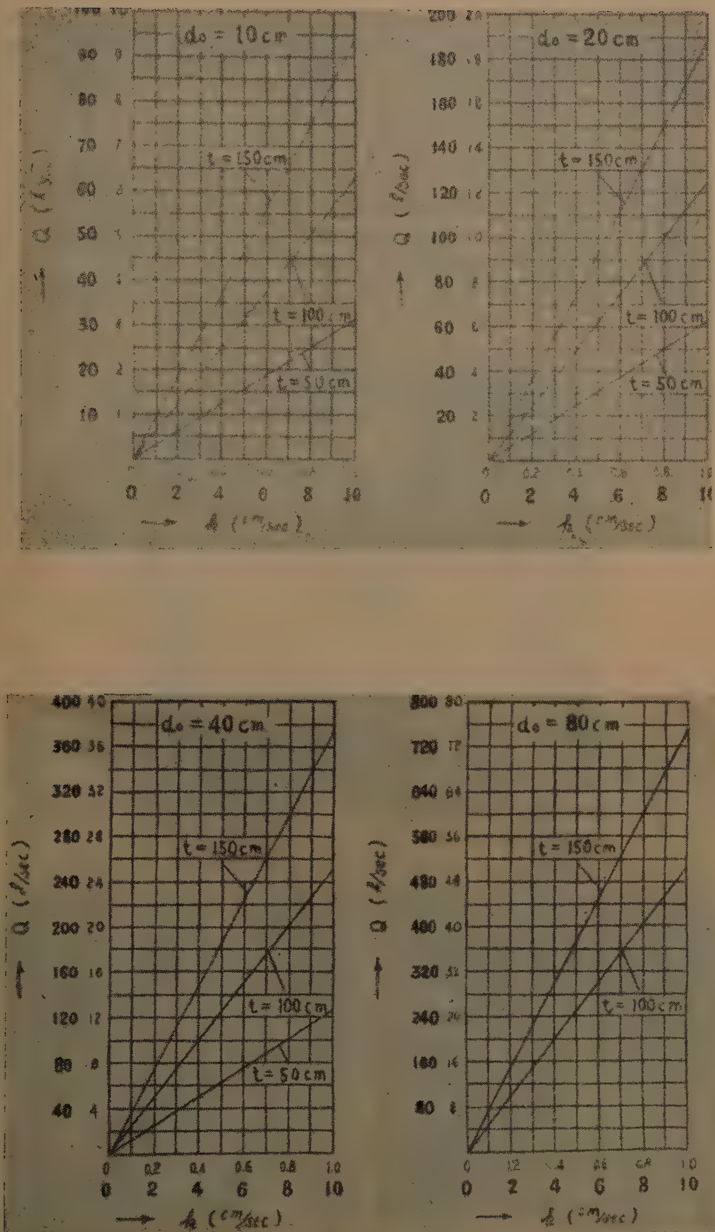


Fig. 3 — Relation between K and Q with assumed d_0 and t.

Pumping is continued on until d_0 becomes practically constant. For the purpose to descriminate whether water-level depression is being caused by pumping or by natural fluctuation, water level is observed for 24 hours before starting to pump and for a period of pumping duration plus 24 hours after stopped pumping. Q is measured by container such as gassoline drum when it is small and by a triangular weir when it is large.

Correlative Check Test

The spherical well method may have its defect in disturbing the aquifer condition to set the well and hence a fatal error might be caused.

To check the error caused by excavation and filling back to set the sphere, coefficient of permeability was determined on comparatively uniform gravel bed,

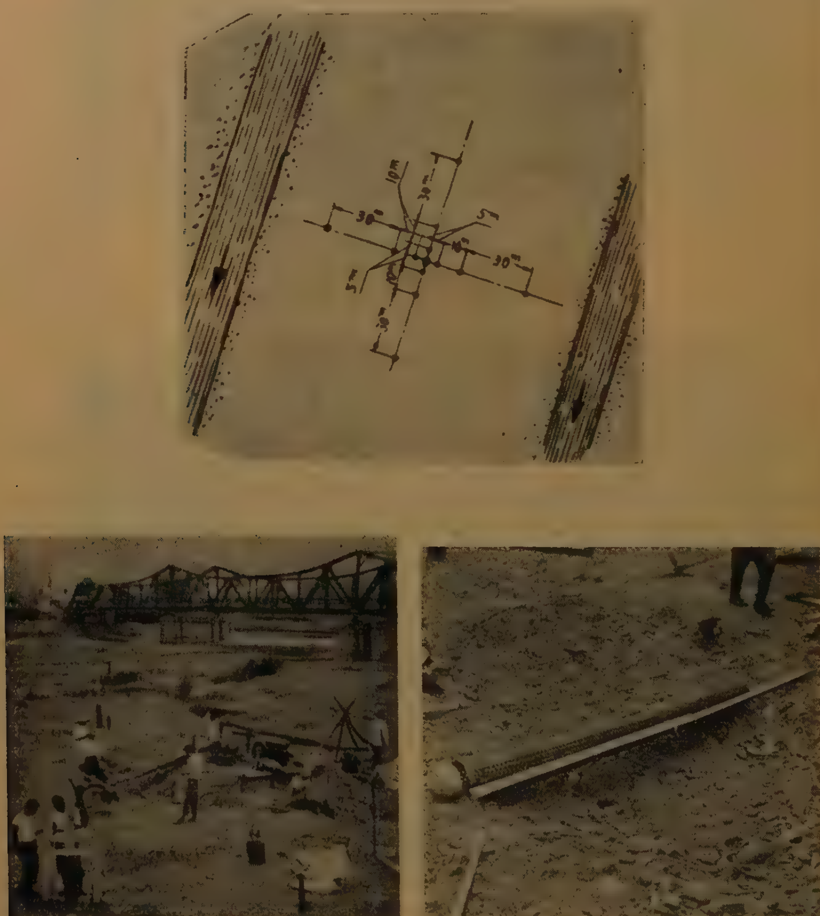


Fig. 4 — Sample Field and Arrangement of Observation Wells.

from the amount of water level depression in the observation wells arranged in known distances from the pumped well. As in almost all practical cases groundwater table is connected to any surface water and the draw down in any well becomes practically constant after a long period of pumping, all equations derived from the assumption that the aquifer be semi-infinite, should be modified to fit the field conditions.

Observation wells were arranged as shown in Fig. 4 and the water-levels were observed simultaneously on all wells every one hour for 24 hours before pumping; with intervals from one to 60 minutes for about 6 hours during pumping and after stopped pumping; and after that every one hour for 24 hours to check and correct the natural fluctuation during the test.

Modification by Field Condition

Fig. 4 is an example of the condition of test field. On three points on the gravelly river-side along the lower Shigenobu River in Shikoku, Japan, permeability determinations by spherical well method and their correlative check test were carried out during August-October 1956. Three test places have similar conditions with minor difference and the equation (1) was modified by S. Kuwabara * as follows:

$$k = \frac{Q}{2\pi d_0}\left\{\frac{1}{t} + \frac{1}{H}\left(\ln\frac{L}{2H} + E + \ldots + 0.4569\right) + 0.3005\,\frac{t^2}{H^3} + \ldots\right\} \qquad (2)$$

where H: the depth of the aquifer

L: distance of pumping well to the surface water

E: Euler's constant $= \lim\limits_{n\to\infty}\left(\sum\limits_{1}^{n}\frac{1}{n} - \ln n\right)$

Kuwabara has also given the deppresion of water level at ordinate r, θ, i.e. $\Delta Z(r, \theta)$ as a function of r, θ, t, H and L from which k can be calculated as follows: in the case $r < H$

$$\Delta Z(r, \theta) =$$

$$\frac{Q}{2\pi k H}\left\{\frac{H}{\sqrt{r^2 + \pi}} + 0.1256 + \ln\frac{L}{2H} - 0.823\,.\,\cos 2\theta\,.\left(\frac{r}{L}\right)^2 + \ldots + \zeta(r)\right\} \qquad (3)$$

where ζ is Rieman's zeta function and in the case $H < r < L$

$$\Delta Z(r, \theta) = \frac{Q}{2\pi k H}\left\{\ln\frac{L}{r} - 0.4516 - 0.823\left(\frac{r}{L}\right)^2\cos 2\theta - \ldots\right\} \qquad (4)$$

In practice observation wells were arranged approximately parallel or rectangular to the river, that is θ be 0° or 90°.

* Mathematical part of this paper was carried out by Shinji Kuwabara, Doctor Course Student at the Physical Institute, Tokyo University and is expected to be made public in other opportunity.

Test Data and Conclusion

Observations were made on each point at two kinds of setting depth t, and the values of permeability obtained by spherical method were referred to those obtained by check tests.

TABLE 1

Permeability test data at Shigenobu site

Place and Test No.	t (cm)	d_0 (cm)	Q (cm^3) × 10^3	L (m)	H (m)	k determined by spherical well, equ. (2)	Obs. well
M — 1	43	12.5	3.55	180	10	1.16	0.98
M — 2	175	32.5	12.50	,,	,,	0.49	0.90
N — 1	115	33	14.35	140	10	0.74	0.64
N — 2	171	14	10.72	,,	,,	0.97	1.14
D — 1	103	64	9.733	140	10	0.29	0.36
D — 2	148	73	7.500	,,	,,	0.14	0.30

It was expected that k will differ by different setting depth t, and that in a comparatively homogeneous aquifer the difference will be small and the check test results is to be correlated on such an aquifer.

Table 1 shows the test results in which test place abbreviated N is regarded comparatively homogeneous, and the values of permeability determined by the spherical method is regarded to agree with those determined by the water levels in observation wells.

The test result on other 2 sites by the spherical method is interpreted to show that permeability differs considerably by bed, and the values calculated by observation well method which represent the permeability of the test site as a gross are not to be correlated to permeability determined by spherical well method.

When the draw down d_0 or discharge Q is small. that is when the actual aquifer can be considered to be very wide, the values of k calculated from equation (1) approach the values calculated by equation (2). And as the sphere is rather small, one may be able to determine the permeability of more thin particular bed.

Many ways of application, for instance using two spheres, one as a source and the other as a sink, will be developed and the sphere with its accessories is expected to be improved.

CORRELATION OF GROUND-WATER LEVELS AND AIR TEMPERATURES IN THE WINTER AND SPRING IN MINNESOTA (*)

ROBERT SCHNEIDER (**)

Abstract

In a study of natural ground-water recharge in Minnesota a close relationship was observed between air temperatures and ground-water levels in the winter and spring. Hydrographs of two wells, one in the south-central part of the State, the other in the northeast, indicate that the water table declines during the winter when the mean daily air temperatures remain below 32° F. Within a few days or less after the air temperature rises above freezing, ground-water recharge begins. If below-freezing temperatures return for some time, the water table again starts to decline.

It has been shown in the laboratory that capillary water and water vapor move in the direction of the thermal gradient. The winter decline of the water table is believed to be caused in part by the upward movement of moisture by capillarity from the water table to the frozen soil, resulting in accretion to the frost layer from below. When the air temperature rises above freezing, the water table begins to rise as a result of downward percolation of melt water from the bottom of the frost layer.

The largest increment of ground-water recharge in Minnesota occurs in the spring. Because of the comparatively great depth of frost penetration and the relatively impervious nature of frost, the initial source of spring recharge is largely frostmelt. The frozen soil impedes or prevents the downward movement of snowmelt and rain. Once the frost layer is dissipated, recharge from infiltrating surface water is facilitated. In addition, the reversal of the temperature gradient results in the downward movement of moisture from the warming soil zone to the water table.

Introduction

The largest increments to ground-water storage in Minnesota commonly occur in the spring. In a study of this recharge phenomenon, a close relationship between air temperatures and water levels in the winter and spring was noted. It is the purpose of this paper to describe the relationship and discuss its significance in the hydrologic cycle.

The study was made as part of a Statewide ground-water investigation by the United States Geological Survey in cooperation with the Division of Waters, Minnesota Department of Conservation, and the Minnesota Iron Range Resources and Rehabilitation Commission.

The water-level data used herein have been published or are in the process of being published as water-supply papers of the Geological Survey. Air temperatures were obtained from records of the U. S. Weather Bureau.

General Pattern of Water-level fluctuations in Water-table wells

The water table in Minnesota is usually at a relatively low level during the winter. In the spring it rises abruptly and generally reaches the highest level of the year. The spring peak is followed by a declining trend during the summer, which is caused

(*) Publication authorized by the Director, U. S. Geological Survey.

(**) District Geologist, Ground Water Branch, U. S. Geological Survey, St. Paul, Minn.

by the large evapotranspirative draft and lateral movement of water toward lakes and streams. Summer and fall rains recharge the soil and ground-water reservoirs, occasionally reversing the downward trend of the water table.

The loww inter water levels have been attributed to the fact that the ground remains frozen, and precipitation, which is largely in the form of snow, cannot recharge the ground-water reservoirs. It is inferred that the decline results from continued natural ground-water discharge, which contributes to the base flow of streams. The spring recharge has been ascribed to the downward percolation of snowmelt and rain.

The present study of water levels and air temperatures suggests that the phenomena of spring recharge and declining winter water levels may involve several factors in addition to those mentioned above.

Relation between Water levels and Air temperatures in the Winter and Spring

The hydrograph of well 108.30.9add, SE 1/4 SE 1/4 NE 1/4 sec. 9, T. 108 N.,

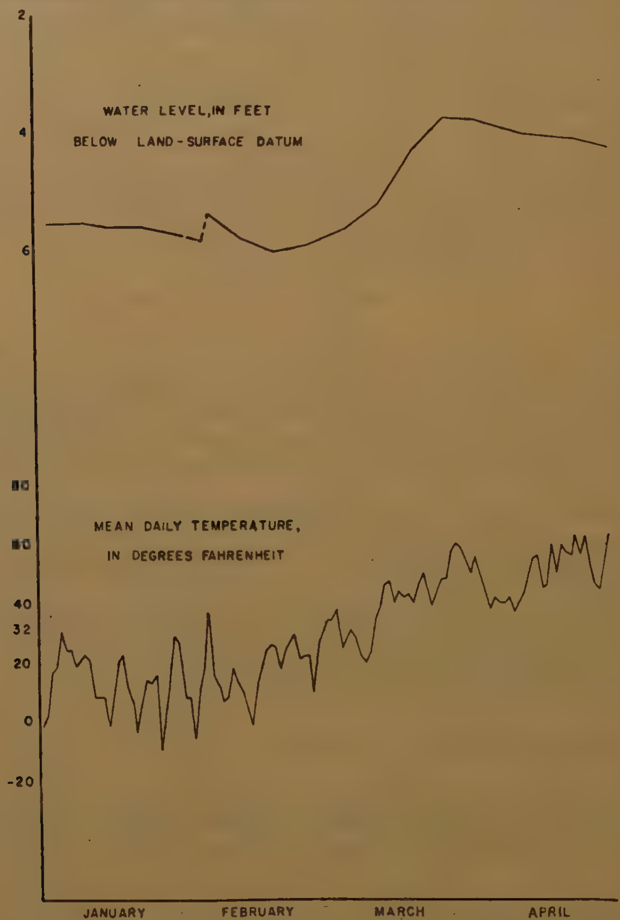


Fig. 1

R. 30 W., south-central Minnesota, was the first used in the study. This well, completed in glacial drift at a depth of 32 feet, has been measured about once each week since 1942, and daily maximum and minimum air temperatures have been recorded at the U. S. Weather Bureau station at New Ulm, Minn., about 10 miles north. Several portions of the hydrograph, which best illustrate the subject of the paper, have been selected for the following discussion.

The water-level record for 1946 (*fig. 1*) indicates a gradual winter decline interrupted by one reversal early in February. This isolated winter reversal can be correlated with a rise of the mean daily air temperature that occurred about the same time (February 5). It should be noted that the mean daily temperature rose slightly above 32° F. Prior to this date, and for almost two weeks afterward, the mean temperatures were generally much lower. The spring rise of the water table began during the last half of February, and, although the mean daily temperature did not rise to 32° F at New Ulm until the end of the month, it is possible that it exceeded 32° F at the well starting about mid-February.

In 1948 the hydrograph (*fig. 2*) indicates a downward trend of the water table

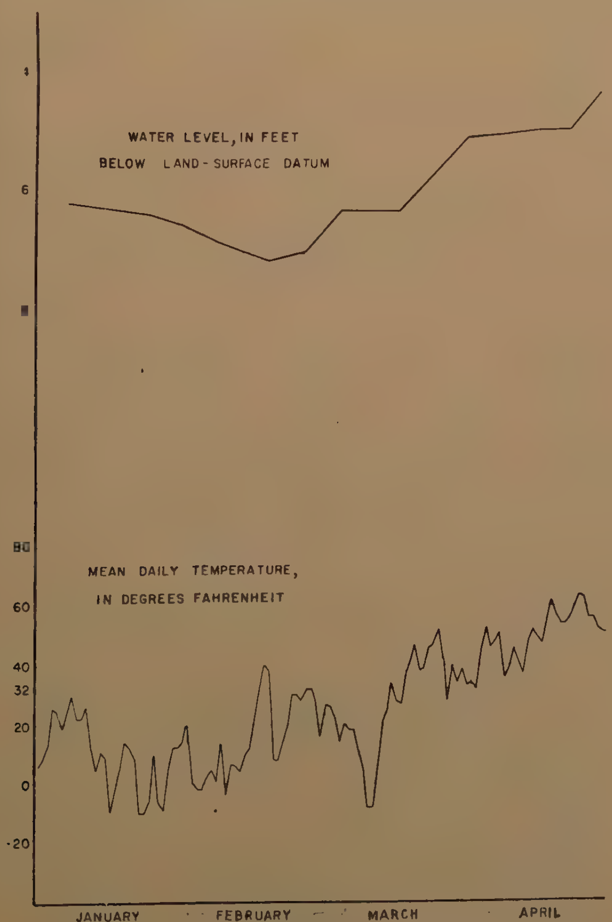


Fig. 2

through January and most of February, during which period the mean daily temperature was well below freezing. The first reversal in the trend of the water level in February can be correlated closely with the time when the mean daily temperature first exceeded 32° F. From the end of February until the middle of March the mean daily temperature again dropped below 32° F, and this is reflected in the «plateau» in the hydrograph for most of the first half of March. During the rest of March and April the water table and temperature continued to rise.

The slight rise of the water table from the beginning of January to the early part of February 1951 (*fig. 3*) has no obvious relation to the temperature record; however it may have resulted in part from infiltrating snowmelt. The decline during most of February is typical of the trend of the water table in the winter. A significant feature of the hydrograph is the abrupt rise that started in the latter part of February. A few days earlier the mean daily temperature exceeded 32° F for the first time that year. The pronounced flattening and slight decline of the hydrograph during March can be correlated with the period of subfreezing mean daily temperatures that started at the end of February.

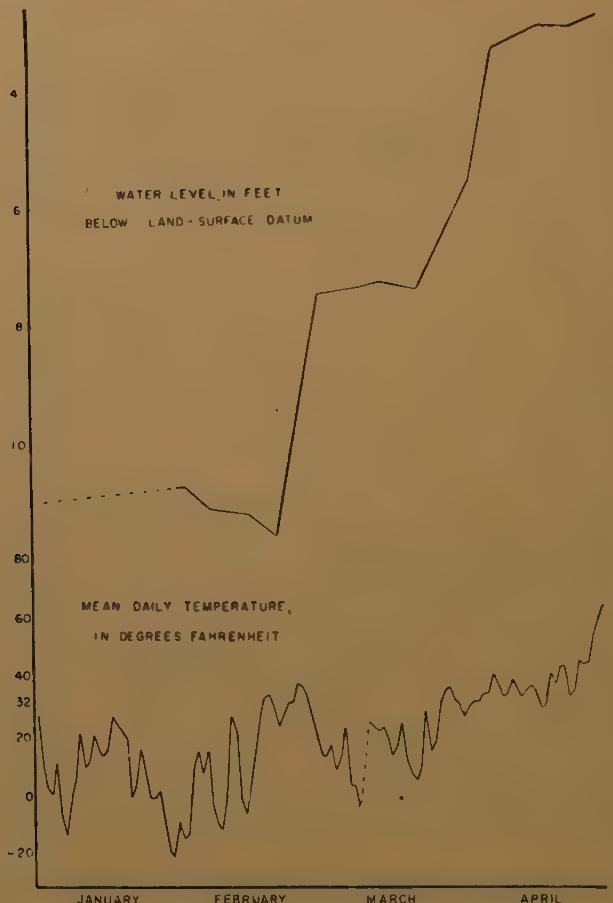


Fig. 3

A correlation between the water level in well 108.30.9add and the air temperature at New Ulm is apparent. It is believed that minor discrepancies can be attributed in part to the long distance between the observation well and the weather station and/or the fact that water-level measurements were made at intervals of one week or longer.

In an attempt to study this phenomenon in greater detail in another area, an observation well equipped with a recording gage in northeastern Minnesota was selected. Well B58.20.16dbcl, SW 1/4 NW 1/4 SE 1/4 sec. 16, T. 58 N., R. 20 W., Chisholm, St. Louis County, is 40 feet deep and taps glacial sand and gravel. The water level is affected by the pumping of two nearby wells, although the pumping regimen is more or less regular. The nearest weather station is about 5 miles southwest, at the Mahoning Mine, Hibbing, Minn.

Although no record was obtained for the precise date of the initial spring rise of the water table in 1954 (*fig. 4*), the start of the rising trend appears to be correlative with the date when the mean daily temperature rose to 32^0 F for the first time that year. Part of the water-level rise in March resulted from the gradual reduction in

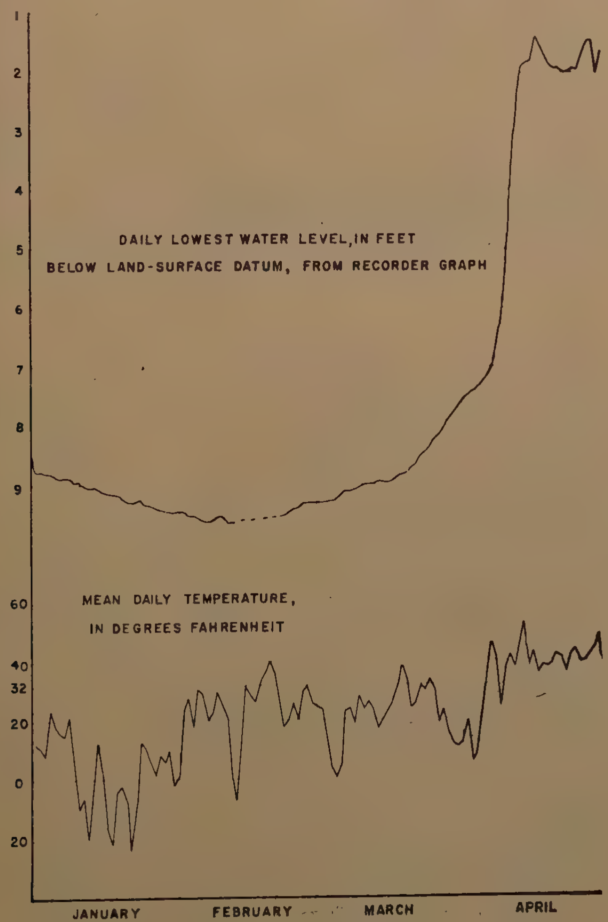


Fig. 4

yield of one of the nearby pumped wells. The drop in temperature to 1° F early in March can be correlated with the relatively flat portion of the hydrograph for about the same period. On April 2 the mean temperature was 6° F, which is the bottom of a «trough» in the thermograph coinciding with a decrease in slope of the rising hydrograph for about the same time interval. The almost vertical portion of the graph, starting early in April, coincides with the time when the mean daily temperature rose well above 32° F and remained above. During part of February and March, when the water level was rising at a lesser rate, the mean temperature fluctuated considerably but was close to 32° F most of the time.

In 1955 (*fig. 5*) the water level dropped steadily from January through March while the mean daily temperature remained well below freezing most of the time. The brief above-freezing period, March 9-10, coincides with a flat portion of the hydrograph. At the end of March the mean daily temperature exceeded and remained above 32° F, and the period of spring recharge started a few days later. The distinct incraese

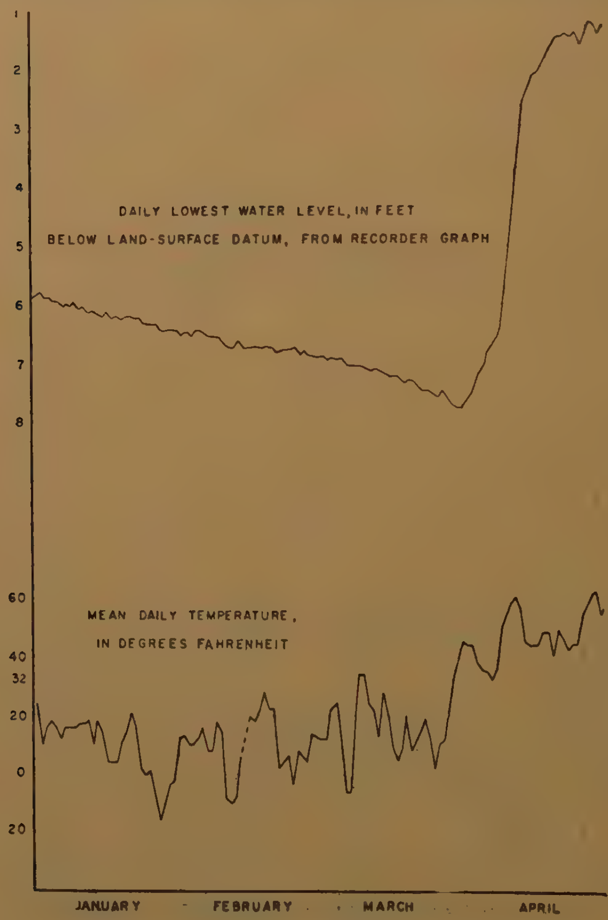


Fig. 5

in the slope of the rising curve early in the second week of April should be noted. This break in slope is quite similar to the one that occurred early in April 1954 (fig. 4).

Despite the long distance between the observation well and the weather station, it is believed that the relationship between water levels and air temperatures is well exhibited by the hydrograph of well B58.20.16dbcl and the temperature data at the Mahoning Mine at Hibbing.

Explanation of Relation between Ground-Water Levels and Air Temperature

As a prelude to an explanation of the relationship discussed above, it is necessary to describe the physical characteristics of frozen soil. The form of the frost layer is influenced by several factors, among which are the type of soil or rock and the moisture conditions.

Storey (1955) describes four types of frozen soil: concrete, granular, honeycomb, and stalactite. Concrete frost structure consists of thin ice lenses and crystals; it is dense and usually associated with freezing to great depths. Granular frost is a loose, porous arrangement of small grains or crystals of ice scattered through the soil; it occurs as a result of shallow freezing. Honeycomb frost is loose and porous; it also is associated with shallow freezing. Stalactite frost consists of many small icicles partly fused into sheets or loosely bound blocks; it is formed during a refreeze of partly thawed honeycomb frost.

Storey states that concrete frost is relatively impermeable. Although the other frost structures described would seem to have little significance so far as percolation of water is concerned, as little as 1 inch of concrete frost prevents infiltration of rain or melting snow. The freezing of heavy-textured soils prevents percolation of precipitation more effectively than frost in light-textured soils.

Melting of the Frost Layer from the Bottom

The rise of the water table in the spring generally has been attributed to the downward percolation of snowmelt and rain. In Minnesota the available data indicate that spring recharge starts within a few days after the mean daily air temperature rises to 32° F. If downward-percolating snowmelt from the land surface were responsible for the initial rise of the water table in the spring, it would be necessary for the relatively impervious frozen soil to thaw within a few days after the air temperature rose to 32° F. Unfortunately, no quantitative data are available on the depth of the frozen soil in the areas under consideration. However, according to a study made at Madison, Wis., by Bay, Wunnecke, and Hays (1952), frost penetration reached depths of 30 to 35 inches under various field conditions in the winter of 1949-50. They indicate also that it took at least two to three weeks from the time thawing started for the frozen layer to dissipate. Climatic conditions at Madison are quite similar to those in the vicinity of well 108.30.9add in south-central Minnesota. Winter temperatures are considerably lower in northeastern Minnesota where well B58.20.16dbcl is located, and it is probable that the depth of penetration of frost in the soil is generally greater than at Madison.

If impermeable (concrete) frost is present, a source other than snowmelt must be responsible for the initiation of spring recharge within a few days after the air temperature rises above freezing. It is believed that, under these conditions, melt water from the bottom of the layer of frozen soil produces the initial rise of the water table in the spring. Also, when the mean daily air temperature rises above freezing periodically during the winter, when the general water-level trend is downward, some melt water from the bottom of the frozen soil descends to the water table. In a study

by the Portland, Me., Water District (Public Works, 1940), it was observed that thawing of the frozen soil, which was 45 inches thick, began at the bottom; a few days later, thawing started at the top. The frost layer disappeared at a depth of 15 inches below the surface after having melted both upward and downward to this depth. In the investigation by Bay, Wunnecke, and Hays (1952) of four sites at Madison, Wis., the frozen layer (30 to 35 inches thick) started to thaw from the bottom first. At each site the frozen layer disappeared at a depth equal to about one-half to one-third the original thickness of the layer.

Capillary Movement of Water to the Frost Zone

Bouyoucos (1915) showed by laboratory experiments that soil moisture moves from a warm to a cold column of soil. He attributed the movement to the increase in cohesion between water particles and in adhesion between water and soil particles that occurs with a decrease in temperature.

Smith (1943) stated that capillary water and water vapor move in the direction of the thermal gradient, and that condensation of vapor, by forming capillary bodies, triggers the capillary movement.

According to Jumikis (1956) Ruckli (1950) published an equation for the depth of frost penetration and stated as one of his assumptions that, under the proper thermal gradient, there is upward «suction» of capillary moisture derived from ground water toward the growing and downward-advancing ice lenses or crystals (frozen soil).

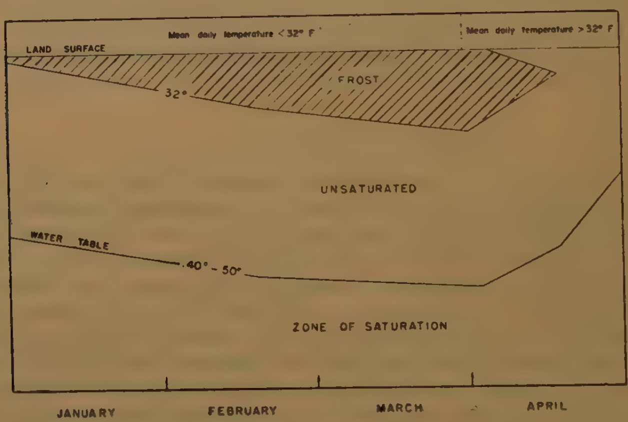


Fig. 6

The sketch in *figure 6* illustrates hypothetical thermal conditions, the trend of the water table, and the occurrence of frost in the winter and spring. In the winter, heat moves upward from the zone of saturation to the atmosphere. The thermal gradient induces the upward movement of moisture which freezes to form the frost layer as heat is continually removed. When the air temperature rises above 32° F, as it would in the spring, heat continues to move upward from the zone of saturation; however, instead of moving through the frozen layer, it starts thawing the bottom of the layer because an opposing thermal gradient now causes heat to move downward from the atmosphere to the frozen soil.

It is concluded, on the basis of the preceding paragraphs, that part of the water-

level decline during periods when the air temperatures are below freezing results from upward movement of moisture from the water table with the thermal gradient. In Minnesota, where the depth of frost penetration is greater than it is in most of the rest of the United States, it would appear that such upward movement accounts for a significant part of the winter decline of ground-water levels and accumulation of frost.

Effect of the Frost Layer on Recharge and Surface-Water runoff

Recharge occurs when the mean daily air temperature rises above 32° F for some time and the bottom of the frost layer starts to melt. Where concrete frost is present, the frozen layer is impervious and impedes or prevents recharge from snowmelt and rain. It is believed that the steepening of the hydrographs of well B58.20.16dbcl early in April 1954 and April 1955 (figs. 4 and 5) occurred when the frost layer finally disappeared and more rapid recharge by snowmelt and rain, as well as by the frostmelt that had been accumulating above the last of the remaining frost, became possible.

Drescher (1955) presents the hydrograph of a shallow well near Hancock, Wis., which was completed in sand and gravel of a glacial-outwash plain. The greatest and most rapid rise of the water level took place at the end of March and the beginning of April 1952, before all the snow melted. In a personal communication (1957), Drescher states that it is doubtful in this case that the frost was completely gone, but it is probable that much of the melting snow found its way to the water table through the frost zone. This interpretation apparently corroborates Storey's statement (1955) that frost in light-textured (sandy) soils is relatively ineffective in preventing percolation of precipitation. The areas under consideration in the present study are underlain largely by dense silty or clayey soils in which concrete frost is likely to form.

The frost layer affects surface-water runoff to a considerable degree. In view of the fact that much of the winter streamflow represents discharge from ground-water storage, thickening of the frost layer, as described above, as well as a declining water table, are contributing factors to the progressive diminution of streamflow during this season. Also, because the frost layer retards or prevents infiltration, it affects surface runoff in another way—it may lead to flooding when heavy winter rains are unable to infiltrate the soil.

Conclusions

It is believed that a significant part of the winter water-table decline in Minnesota is the result of upward movement of capillary moisture to the frost layer, which is thickened by accretion from below. The movement is in response to the thermal gradient and it starts when the mean daily air temperature declines in the late fall and early winter. Within a few days after the air temperature rises above 32° F, the water table begins to rise as a result of downward percolation of frostmelt from the bottom of the frost layer.

In the spring the initial source of recharge in areas of dense soil and concrete-type frost is frostmelt because the frost impedes or prevents the downward movement of snowmelt and rain. After the frost layer disappears, the main source of recharge is infiltrating surface water. Because of the reversal of the temperature relations, downward movement of moisture will be accelerated by a downward temperature gradient.

REFERENCES

Bay, C. E., Wunnecke, G. W., and Hays, O. E., 1952, Frost penetration into soils as influenced by depth of snow, vegetative cover, and air temperatures: *Am. Geophys. Union Trans.*, v. 33, no. 4.

Bouyoucos, G. J., 1915, Effect of temperature on movement of water vapor and capillary moisture in soils: *Agr. Research Jour.*, v. 5, no. 4.

Drescher, W. J., 1955, Some effects of precipitation on ground water in Wisconsin: *Wisconsin Geol. Survey Inf. Circ.* 1, p. 12.

Jumikis, A. R., 1956, The method of solution of Ruckli's frost-penetration equation: *Am. Geophys. Union Trans.*, v. 37, no. 2.

Paulsen, C. G., and others, 1949, Water levels and artesian pressure in observation wells in the United States in 1946; Part 3, North-Central States: *U. S. Geol. Survey Water-Supply Paper* 1073.

—, 1951, Water levels and artesian pressure in observation wells in the United States in 1948; Part 3, North-Central States: *U. S. Geol. Survey Water-Supply Paper* 1128.

Public Works, 1940, Buried thermometers register depth of frost in clay and gravel soils: *Public Works*, v. 71, no. 8, p. 40.

Ruckli, R., 1950, Der Frost im Baugrund, Vienna, Springer Verlag.

Sayre, A. N., and others, 1954, Water levels and artesian pressures in observation wells in the United States in 1951; Part 3, North-Central States: *U. S. Geol. Survey Water-Supply Paper* 1193.

—, 1956, Water levels and artesian pressures in observation wells in the United States in 1954; Part 3, North-Central States: *U. S. Geol. Survey Water-Supply Paper* 1323.

—, 1957, Water levels and artesian pressures in observation wells in the United States in 1955; Part 3, North-Central States: *U. S. Geol. Survey Water-Supply Paper* 1406.

Smith, W. O., 1943, Thermal transfer of moisture in soils: *Am. Geophys. Union Trans.*, v. 24, pt. 2, p. 511-524.

Storey, H. C., 1955, Frozen soil and spring and winter floods, *in* Water, The Yearbook of Agriculture: *U. S. Dept. of Agriculture*, p. 179-184.

U. S. Weather Bureau, 1946, 1948, 1951, 1954, and 1955, Climatological data, Minnesota.

STATUS OF GROUND-WATER STUDIES IN CANADA

J. F. CALEY and K. POLLITT

Abstract

Ground-water studies in Canada were initiated by the Geological Survey of Canada in 1903. Investigations during the first 30 years were confined almost solely to the provinces of Manitoba. Saskatchewan and Alberta. More recent surveys have embraced nearly every province in Canada.

The provinces of Alberta, British Columbia, Ontario and Quebec carry on ground-water studies which are independent of Federal programs. Ontario was the first to enter the field in 1945.

Ground-water studies are a necessity for a full understanding of the hydrology of Canada and so aie essential in the planning of settlement and industry in our country.

A HYDROGEOLOGICAL SURVEY IN BRITISH HONDURAS

C. G. DIXON

ABSTRACT

The author outlines some aspects of a survey of groundwater supplies carried out by him during the years 1953 to 1955, and the methods employed are described. The area studied is underlain by limestones and marls, some of which, especially the more superficial marls, contain gypsum and common salt. Seasonal drying of the dug-wells of the villages imposes an acute problem which affects rural settlement. Periodic visits were paid to dug-wells dispersed over a wide area and measurements were taken of the level of the water below temporary bench marks. Samples of the water were taken and analysed. In this manner seasonal fluctuations of the water table were observed and changes in the quality of the water were determined. These were related to monthly rainfall statistics and also to the nature of the geological formations in which the water was found. The height of the water table at its highest and lowest seasonal levels was indicated on a map by contours.

The author states that swamps are an important factor in maintaining adequate supplies of potable water for such small communities as villages and these supplies might be improved by making it easier for swamp water to soak downwards and improve the underground storage for the dry season. The author concludes by stressing the importance of the regular and systematic collection of data relating to ground water. In British Honduras this would not be a difficult task.

There are few fields of geological investigation whose results are more readily appreciated by public authorities than water supply surveys, because the information obtained has a direct application to the problems which confront those who have to find potable water in adequate quantities and deliver it to rural or urban communities. In recent years it was the good fortune of the writer, as Government Geologist in British Honduras, to carry out an investigation of the ground water resources of part of that country. The perennial problem of water shortage in villages and towns alike, which occurs regularly every year towards the end of the dry season, when wells dry up, impelled the Government to examine the situation with a view to finding out what could be done to improve the domestic supplies of water.

NATURE OF THE PROBLEM

The difficulties are twofold: (*a*) the quality of the water is very bad throughout most of the northern part of the Colony; (*b*) the dug-wells dry up during the dry season so that many villages may be almost without water, especially near the end of the dry season. This state of affairs is especially true in the northermost part of the Colony in the areas underlain by white marls and coastal deposits. In areas where hard rock lies near the surface of the ground, the efforts of the villagers to dig wells are often defeated by the hardness of the rock. It is probable that even when bore-hole supplies are made available, the problem of rendering it suitable for domestic consumption may still have to be solved.

As ground water supplies are developed, the question often arises as to how the quality and quantity of water available can be maintained or improved. This is especially liable to be true in British Honduras, where there is, in the limestone areas of the lowlands, abundant water of very indifferent quality but relatively little that is of tolerably good quality. It is important that the factors which determine the quality

of the water should be fully understood. It is also desirable that it should be possible to assess the potential resources of a subterranean source of water, and to forsee how it might be possible for wrong practices to spoil the supply.

Factors affecting Ground Water

The geology of British Honduras has already been described by Ower (1928), Flores (1952) and Dixon (1955). The areas with which we are concerned are the more populated lowland areas of northern British Honduras, north of the Maya Mountains. This part of the country is underlain by limestone which, over a large part of the area, is overlain by superficial deposits of estuarine marls and clays. These superficial deposits, especially the youngest of them along the river valleys, contain notable amounts of gypsum and common salt. Consequently, in marl, the water which lies near the surface is often of very poor quality.

Most of the area which received the closest attention is at less than 60 feet elevation, and much of it is only a few feet above mean sea level.

Agriculture is the principal occupation of the rural population and they live in small villages whose domestic water is drawn from shallow dug-wells which are constructed by the villagers themselves. These wells rarely exceed 40 feet in depth and most are much less, and each householder usually has his own well in his own backyard.

The average annual rainfall over the past ten years in northern British Honduras is between 50 and 60 inches. It is unequally distributed throughout the year and the dry season lasts from February till May, during which period the monthly rainfall is usually only an inch or two. There is also considerable variation in the rainfall from one year to the next. But it is not just the totals that are important from the point of view of water supply; the frequency of showers during the dry season was found to have a strong influence on the amount of dissolved matter in the ground water. The more frequent the showers are the better the water is, and it appears that the amount of rain which falls during the wet season may be of less importance than that there should be at least some heavy showers during the long dry spells.

Evaporation and transpiration must account for most of the water lost from the ground during the dry season and the roots of trees must be able to reach the moist ground above the saturated layer.

Methods employed during the Survey

Fortunately northern British Honduras has two good main roads and a quite satisfactory system of feeder roads. Motor transport was provided to make it possible to make frequent visits to the villages. Numerous dug-wells were selected at convenient places along the roads, and these were numbered. Levelling surveys were carried out and temporary bench marks were established at the numbered wells. By this means it was possible to express the height of the surface of the water in the well in feet above mean sea level.

The visits to the wells were made every four to six weeks and measurements and dates were noted on a form. Samples of water were taken from the well, lagoon or river as the case may be. For each well there was one page on which all observations, including the results of the chemical analyses, were recorded. By the time the observations had extended over two years it became possible to draw reasonably safe conclusions.

The Government maintains a number of stations in various parts of the country

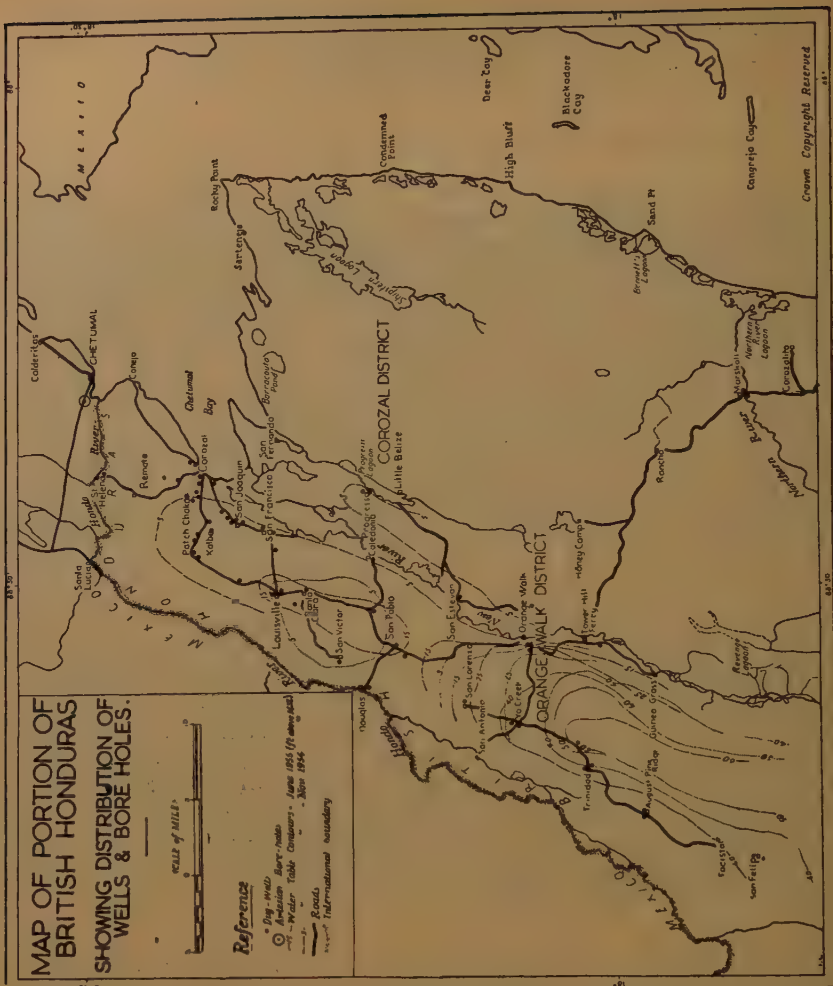


Fig. 1

where daily rainfall measurements are recorded, and this information proved invaluable in assisting in interpreting the variations of the level of the water table and the quality of the water.

At a later stage in the investigation, contours were drawn on a map on the scale of a quarter inch to the mile, so as to illustrate the form of the water table at its highest and lowest levels during a year. The intervals chosen were somewhat irregular but mostly every 10 feet. This was done to suit the results actually obtained, because it was considered that to confine oneself to the same contour interval might entail too much interpolation and so render the map somewhat hypothetical.

Using the data obtained from the levelling and chain survey, profiles of the roads were drawn on a horizontal scale of 1 inch = 200 feet and a vertical scale of 1 inch = 100 feet. The positions of the wells were drawn on the profiles and so

also was all geological information it had been possible to gather from surface observations and what was known of the strata penetrated when the wells were being dug. In the latter connection the villagers proved to be most helpful and they had an intimate knowledge of the strata penetrated by the wells.

The analyses of the water taken from rivers was very useful in that they not only provided information on the quality of river water, but showed clearly how the sea water creeps upstream during the dry season. For instance, the New River stops flowing in the dry season, and it was found that the front of the sea water crept up the river at about one mile per day. During the year 1955 the salt water reached a point 40 to 50 miles upstream from where the river enters the sea.

When the water samples were analysed, quantitative estimations were made the content of sulphate, chloride, total hardness and total dissolved solids. Temporary and permanent hardness were not always estimated separately. The results were all expressed in parts per million.

It should be noted that the equipment used was very limited and the observations made and chemical analyses carried out were sufficiently simple for it to be quite easy to train a technical assistant to carry out most of the work involved. Anyone with a secondary school education could do it under supervision, but the results obtained were invaluable.

Quality of Water in relation to Geology

White Marl Areas. The worst water was found in white marl. The total hardness ranged between 300 and 1300 parts per million but was most often between 300 and 650 p.p.m. The sulphate varied much according to the locality and ranged between 50 and 700 p.p.m. but 100 to 400 p.p.m. was more usual. Chloride was usually less than 80 p.p.m. but there were many restricted areas where it was found to be as high as 175 p.p.m.

Limestone Areas. Sulphate was generally present in only negligible amounts but the total hardness was usually between 150 and 500 p.p.m., 250 to 350 p.p.m. being usual. More than half of the hardness could be removed by boiling the water for about 5 minutes. Chloride was not present in amounts that were in excess of the acceptable limit of 50 p.p.m.

Other Conclusions drawn

As a rule the water table rises and falls by about five feet, but the fluctuation was more in some places, especially under watersheds and in ground whose elevation was more than 50 feet above mean sea level.

The seasonal variations in the amount of dissolved matter in the water did not usually follow a very obvious pattern, but this is probably because the observations did not extend over a sufficiently long period. The seasonal fluctuations during one year are not so great as the changes that may occur over a period of several years. For example, at one well at Louisville, not far from the town of Corozal, he readings extended from September 1953 until June 1955. The hardness at this well was between 700 and 900 p.p.m. during the dry season of 1954 but only half that during the same period in 1955. The high degree of hardness in the early part of 1954 may perhaps be partly explained by the fact that 1953 was a year of drought when little more than half the usual amount of rain fell during the latter part of that year.

Briefly then the changes in the salinity of the water partly usually reflect seasonal

variations of rainfall, but further complications arise from variations from year to year, and the frequency of showers during the dry season often appeared to be another important factor.

Over most of the northern part of British Honduras, within 10 to 15 miles of the coast, the water table drops to within a foot of mean sea level, by the end of the dry season. But farther inland its elevation at that time of the year is higher, at least under the watersheds.

The water table also tends to be higher beneath extensive swamp lands than it is under the drier ground some distance from the swamp.

The Role of Swamps in relation to Water Supply

It is clear that for shallow dug-wells swamps are an important factor in maintaining supplies of good quality water which may be used for domestic purposes.

Belize, the capital, now receives most of its water from several dug-wells situated in swampy land several miles outside the city. There are five such wells, only two of which had been put into use by the end of 1955. The remainder of the water required by Belize is still obtained, as formerly, by roof catchment. The total hardness of the town supply was 250 p.p.m., with relatively little sulphate at the end of the dry season in 1955, and fell to 130 p.p.m. by the end of August.

At a few villages in the white marl country similar conditions were noted. A few villages situated close to swamps had good water for most of the year while other villages in the neighbourhood had water that was of very poor quality.

It is unfortunately often the case that whenever some planning authorities see a swamp they want to drain it in order to provide land for building or agricultural purposes. There is a marked tendency for the better water beneath swamps to become exhausted towards the end of the dry season. This might be avoided if the drainage of the swamps is impeded, especially during the dry seasons. In this way more rain-water would have a chance to percolate downwards to increase the reserves under-ground. This downward percolation might be greatly increased by digging pits or wells in the swamps and filling them with boulders, gravel or some other porous material.

The writer is aware of one case where a new community was planned to be built near a group of wells which yielded reasonably good water, and it was proposed that the swamp be drained. Fortunately the writer was able to warn the authorities that to drain the swamp would result in impairing the very supply of water which caused them to select that site for the new community.

For rural farming communities in the tropics, swamps need not necessarily be regarded as waste land, especially if it is allowed to go back to forest and so provide the villagers with a very handy source of thatch and firewood near their homes, in addition to acting as a catchment for recharging the subterranean reservoirs.

Collection of Data

A great deal of very valuable information on ground water can be collected very easily by semi-skilled personnel, and the equipment required is not expensive. Observations on any one area must extend over a period of several years, preferably five, and daily rainfall records must be available for a reasonable number of places within the area. The observations on the ground water should be made about once every month and on every occasion samples of the water should be taken and analysed.

REFERENCES

Ower, L. H. (1928). «Geology of British Honduras.» *Journal of Geology*, Vol. 36, p. 494-509.

Flores, G. (1952). «Geology of Northern British Honduras.» *Bull. Amer. Ass. Pet. Geol.*, Vol. 36, No. 2.

Dixon, C.G. (1955). «Geology of Southern British Honduras; — with notes on adjacent areas.» 85 pp. Survey Dept., Belize, British Honduras.

ON THE THEORY OF FLOW OF MISCIBLE PHASES IN POROUS MEDIA

A. E. SCHEIDEGGER (*)

ABSTRACT

The mechanics of one fluid contaminating another in a porous medium is physically a case of miscible displacement. A theory of such miscible displacement can be obtained by an extension of the writer's statistical model of flow through porous media. If the two flowing phases are assumed to have equal density and viscosity, it is the phenomenon of physical dispersion which governs the mechanics of flow. This dispersion has the effect that in a linear displacement experiment the front becomes diffuse and has the shape of an error integral. The degree of dispersion depends on the flow velocity; for this dependence, two limit cases can be given. The theory is compared with a number of experiments reported in the literature and it is shown that the theory is thereby substantiated.

1. INTRODUCTION

Much attention has recently been paid to the displacement of a fluid in a porous medium by another which is completely miscible with it. Cases where this occurs include not only the recovery of oil from reservoirs if solvents are used as displacing agents, which is at present under much discussion, but also the intrusion beneath oceanic islands of salt water into the fresh water lens if the latter is being tapped for water supply purposes, and the spread of radioactive wastes from dump reservoirs into surrounding groundwater-bearing strata.

In contrast to the theory of simultaneous flow of immiscible fluids, which is now fairly well established, the simultaneous flow of miscible fluids in porous media still exhibits some poorly understood phenomena of striking peculiarity. Experiments show that the phenomenon of physical dispersion of the flowing particles away from their mean flow paths is of prime importance. This dispersion governs the degree of mixing of the two fluids at the «interface» and hence the length of the saturation «front» in a displacement experiment. This is quite in contrast to the phenomenon of immiscible displacement which is governed primarily by capillaric effects: The spread of the interface is determined by the amounts of displaced fluid retained behind the front owing to the action of capillarity.

The importance of dispersion in miscible displacement has been established by various experimenters. Yuhara (1954) displaced fresh water by salt water from a column of sand and showed that the resulting front has a spread corresponding to a simple solution of a dispersivity equation; Von Rosenberg (1956) made similar experiments, but using benzene and ethyl-n-butyrate and obtained the same result. Subsequently, Day (1956) calculated an integral of the writer's fundamental differential equations corresponding to a linear flood in order to compare it with an experiment wherein again fresh water was displaced by salt water, confirming the earlier findings qualitatively and finally, Rifai et al. (1956) made a very careful set of experiments whereby a tracer substance was introduced into a seepage system which established it beyond doubt that the distribution of concentration corresponds to that postulated by those theories of flow through porous media which are based upon the hypothesis of complete disorder (Scheidegger 1954, 1955, 1957).

(*) Dr. A. E. SCHEIDEGGER, Imperial Oil Limited, Calgary, Canada.

Whereas it thus appears quite certain that it is the phenomenon of dispersion which is causing the spread of the concentration front, some uncertainty still exists concerning the explanation of the magnitude of this dispersion. The various experiments cited above yield different values for same, and it has been suggested by Rifai (Rifai et al. 1956) that it may be the relative importance of molecular sideways diffusion within each microscopic flow channel which might cause this variety of observations. Rifai arrived at this conclusion statistically by considering a rather specialized model of flow within each flow channel: flow was assumed to take place only down the center of each capillary, the rest is «dead water». If there is enough time for the flowing water to mix with the dead water, one limit case is obtained; — if there is not sufficient time, another limit results. Experimental observations, then, will be expected to lie within the two limits which corresponds indeed to the observations reported in the literature.

Rifai's model, although a rough approximation to Sir Geoffrey Taylor's (1954) theory of miscible penetration of a fluid into one capillary filled with another fluid, is not as general as one might desire. Therefore, it is the purpose of the present study to demonstrate that Rifai's conclusion also follows under quite general conditions from a statistical theory assuming nothing more but complete disorder in the porous medium and laminar flow in the fluid. The idea of Rifai to consider two limit cases, properly adapted to the hypothesis of complete disorder, therefore nicely rounds out the writer's original statistical theory in which only one of the two limit cases had been considered.

2. The Phenomenon of Dispersion

The postulate of the occurrence of dispersion during the flow of fluids through porous media is characteristic of statistical theories. In these statistical theories (Scheidegger, 1955), the fluid is considered as a continuous medium of whiche ach point has a flow path. Each such point is called a «particle», but it should be understood that this has nothing to do with the actual molecules of the fluid. The fundamental problem is to find equations of motion for the probability-density of the position of all the particles of the fluid. Here, «probability» is understood with regard to a ficticious ensemble of porous media consisting of a great number of specimens of identical macroscopic properties.

The problem of determining the probability density of all particles of the fluid is a very complex one. However, the problem becomes tractable if some reasonable assumptions are made. Thus, if the porous medium is assumed as isotropic and, macroscopically, homogeneous; and if different parts of the porous medium are assumed as macroscopically identical, then it is apparent that the probability-distribution function in a homogeneous force field is Gaussian: (cf. Fig. 1)

$$\nu(\mathbf{x}, t) = (4\pi D t)^{-3/2} \exp\left\{-(\mathbf{x} - \langle\mathbf{x}\rangle_{A\nu})^2/(4Dt)\right\} \tag{2.1}$$

where x is the position-coordinate of the particle, t is time $\langle\mathbf{x}\rangle_{A\nu}$ is the vector of average position (over the ensemble) of the fluid particle and D is a measure of dispersion, called «factor of dispersion». The fact that the probability-distribution in Eq. (2.1) is Gaussian is a consequence of the central-limit theorem of the theory of probability.

In the theory of laminar flow, the connection between the average displacement $\langle\mathbf{x}\rangle_{A\nu}$ and the field of forces can be calculated as follows. The field of forces is assumed to be, for the moment, time-independent and homogeneous; viz. equal to

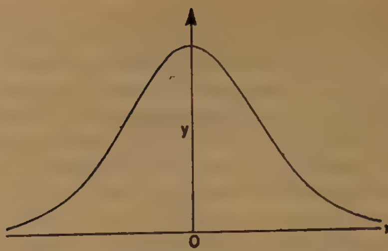


Fig. 1 — Gaussian distribution curve.

grad p. Splitting the time interval into N small steps, one can write

$$\langle x(t = N\tau)\rangle_{Av} = N\,\langle \xi \rangle_{Av} \tag{2.2}$$

where ξ is the displacement during τ. Then, in the case of laminar flow, the flow law is expressed as follows

$$\frac{1}{\tau}\,|\xi| = \frac{B}{\mu}\,|\mathrm{grad}\,p|\ \cos\theta \tag{2.3}$$

Herein θ is the angle between the vectors ξ and grad p, p is the pressure, μ the fluid viscosity and B some constant of the channel.

Equation (2.3) is now to be averaged over the ensemble. The average $\langle\xi\rangle_{Av}$ will be in the direction of -grad p if the porous medium is assumed to be isotropic, as this is the only distinct direction. Its magnitude will be the average of the component of ξ in the direction of -grad p, i.e. equal to the average of $|\xi|\cos\theta$. Thus, one has

$$\langle\xi\rangle_{Av}/\tau = -\frac{1}{\mu}\,\langle B\,\mathrm{grad}\,p\cos^2\theta\rangle_{Av} \tag{2.4}$$

or:

$$V = -\frac{1}{\mu}\,\langle B\,\mathrm{grad}\,p\cos^2\theta\rangle_{Av} \tag{2.5}$$

where V is now the pore-velocity vector. Therefore, the probability distribution can now be expressed as follows:

$$v(x, t) = (4\pi Dt)^{-3/2}\exp\left\{-[x + \frac{1}{\mu}\,t\,\langle B\,\mathrm{grad}\,p\cos^2\theta\rangle_{Av}{}^2/(4Dt)]\right\} \tag{2.6}$$

The average position of the median $\langle x\rangle_{Av}$ of this distribution is:

$$\langle x(t)\rangle_{Av} = -t\,\frac{1}{\mu}\,\langle B\,\mathrm{grad}\,p\cos^2\theta\rangle_{Av} \tag{2.7}$$

Thus, the mean pore velocity is:

$$V = -\frac{1}{\mu}\,\langle B\,\mathrm{grad}\,p\cos^2\theta\rangle_{Av} \tag{2.8}$$

This can also be written as

$$V = -\frac{k}{\mu P}\,\mathrm{grad}\,p \tag{2.8a}$$

if all quantities pertaining to the porous medium are taken into the constants k and P

(Darcy — permeability and porosity, respectively). Then Eq. (2.8a) corresponds to Darcy's law which is thus shown to be valid for mean flow even in dispersive systems.

The above statistical theory refers to homogeneous forces only, but it is easy to effect a generalization to inhomogeneous forces by observing that the fundamental probability distribution v is a solution of the following differential equation:

$$\frac{\partial v}{\partial t} = \Delta (\mathrm{D} v) + \mathrm{div}\ (v \langle \mathrm{B}\ \mathrm{grad}\, p \cos^2 \theta \rangle_{\mathrm{A}v}) \tag{2.9}$$

which is also valid for inhomogeneous forces. Finally, if the continuity condition is expressed, one ends up, by a procedure analogous to that outlined in an earlier paper of the writer's (1955) with

$$\frac{\partial \rho}{\partial t} = \Delta (\mathrm{D} \rho) + \mathrm{div}\ \frac{1}{\mu}\ (\rho \langle \mathrm{B}\ \mathrm{grad}\, p \cos^2 \theta \rangle_{\mathrm{A}v}) \tag{2.10}$$

The above statistical theory of laminar flow through porous media yields a theory of miscible displacement in porous media, if the probability $v(x, t)$ of a «particle» to be at a certain point x at a time t is identified with the «concentration» c of an invading fluid within that originally contained in the porous medium. This is, of course, only possible if the two fluids have (almost) identical physical properties. An experiment embodying such a case could be visualized as follows. Consider a linear system (linear coordinate x) filled with fluids. At time $t = 0$ one starts out with a sharp front of one fluid at $x = 0$, at $x < 0$ there is a constant concentration $c = 1$ of that fluid, at $x > 0$ zero concentration of that fluid (i.e. the medium is fully saturated with another fluid). The two fluids are assumed as miscible. The porous medium is thought to extend to infinity linearly in the direction of x and $-x$.

At time $t = 0$, one starts imposing a (pore) velocity V upon the system directed toward increasing x. Then, the concentration of the fluid originally confined to $x < 0$ can be calculated from Eq. (2.1) at any later time. One obtains (Day, 1956)

$$c = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}\, dz \tag{2.11a}$$

with

$$\mathrm{Z} = \frac{x - \mathrm{V}t}{\sqrt{4\ \mathrm{D}t}}\ . \tag{2.11b}$$

These relationships can be interpreted by saying that the «length» of the concentration front in a linear displacement experiment is proportional to $\sqrt{\mathrm{D}t}$. The length of the front, of course, means that length over which a definite change in concentration,

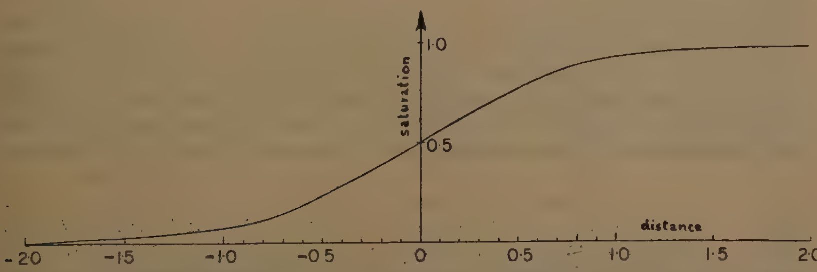


Fig. 2 — Theoretical shape of the front in a linear displacement experiment involving miscible phases (saturation versus distance).

say 80%, occurs. It furthermore turns out that the front has always the same qualitative shape, independently of D; it has always the shape of a Gauss integral (See Figure 2). This is in agreement with the various experiments reported in the literature which all show that the front is properly described by Eq. (2.9). This must be considered as a great success of the statistical theory outlined here.

3. The Factor of Dispersion

The discussion up to the present point does not in the least depend on the particular expression for D. In order to obtain a complete understanding of the dispersion, it will now be necessary to obtain a quantitative expression for D in terms of microscopic flow quantities.

In order to do this, there are two possible procedures which constitute two limiting cases: (*a*) a dynamic procedure, and (*b*) a geometric procedure (see Scheidegger, 1957).

(*a*) *Dynamic procedure.* The dynamic procedure consists in writing down Newton's law of motion for a small element of the fluid

$$\mathbf{B}\,\mathbf{f} - \rho\,\ddot{\mathbf{x}} = \mu\,\dot{\mathbf{x}} \qquad (3.1)$$

where f is the force per unit volume (apart from the viscous forces) and B is the microscopic resistance to flow assumed proportional to the flow velocity. Dots denote time derivatives. The crux of the method is the assumption that this quantity B is equal to that denoted by the same letter in Eq. (2.3). This, in fact, is an adequate picture of the phenomenon only if it is permissible to consider the flow as channel-like, i.e. as taking place in narrow channels whereby a cross-section in each channel can be assumed as uniform. This is the case if there is sufficient molecular sideways diffusion to effect this; — i.e. if one is considering the limiting case where there is enough time in each flow channel for complete mixing by molecular sideways diffusion to take place. Longitudinal molecular diffusion, however, is always assumed as equal to zero.

If the dynamic procedure for calculating the factor of dispersion is carried through starting from Eq. (3.1), the result is (Scheidegger 1954)

$$\mathrm{D} = \frac{\rho a'}{\mu^2}\,(\mathrm{grad}\,p)^2 \qquad a)3.2)$$

where a' is a constant of the porous medium which may properly be termed the latter's (dynamic) dispersivity.

(*b*) *Geometric procedure.* One obtains a different method for calculating D by assuming that there is absolutely no exchange between particles in adjacent streamlines in any one channel (see Scheidegger, 1957). This is, in fact, the condition which one would expect to prevail in *true, laminar flow*. This has the effect that in Eq. (2.1) the distribution v as a function of position (i.e. with x and $\langle \mathrm{x} \rangle_{\mathrm{Av}}$ as argument) must be independent of the flow velocity. Thus, eliminating t from Eq. (2.1) by means of

$$t = |\langle x \rangle_{\mathrm{Av}}| \,/\, |\mathrm{V}|$$

yields

$$v\,(\mathrm{x}, \langle \mathrm{x} \rangle_{\mathrm{Av}}) = \left[4\pi \mathrm{D}\frac{|\langle x \rangle_{\mathrm{Av}}|}{|\mathrm{V}|}\right]^{-\frac{1}{2}} \exp\left\{\frac{-(\mathrm{x}-\langle \mathrm{x} \rangle)^2}{2\mathrm{D}\,|\langle x \rangle_{\mathrm{Av}}|\,/\,|\mathrm{V}|}\right\}$$

which is independent of V only if

$$D = \text{const.}\,|\,V\,|$$

Furthermore, using (2.8*a*), this yields

$$D = \frac{a''}{\mu}\,|\,\text{grad}\,p\,| \tag{3.2b}$$

where a'' is another constant of the porous medium, preferably called its geometrical dispersivity.

A result analogous to (3.2*b*) has also been found by Rifai (cf. Rifai et al., 1956) as outlined above, but the present deduction shows that the specialized assumptions made by Rifai are, in fact, not necessary.

4. Conclusion

Surveying the formulas extant from the above-outlined theory of flow of miscible phases in porous media, the principal results and their relationship to observations may be summarized as follows.

(i) In a linear displacement experiment, the shape of the front is that of an error integral corresponding to Eq. (2.11) (See Figure 2). This result has been confirmed by experiments to a high degree of accuracy.

(ii) The magnitude of the factor of dispersion D lies theoretically between two limits which may be represented as follows:

$$\text{case } (a) \qquad D \sim V^2 \tag{4.1}$$

$$\text{case } (b) \qquad D \sim V \tag{4.2}$$

Herein, case (*a*) presumably represents the case where there is enough time for complete mixing of invading and original fluid in each flow channel by molecular sideways diffusion, whereas in case (*b*) there is not enough time. Longitudinal diffusion within individual flow channels has been neglected in any case.

The experimental results seem indeed to confirm that D lies within the two limits indicated by Eqs. (4.1) and (4.2). Furthermore, it is also known that a characteristic time exists in miscible displacement experiments (often called «stabilizing time») which separates domains of different behaviour of the front. This could be thought to correspond to the theoretical «diffusion time» separating case (*a*) from case (*b*).

(iii) For case (*a*) and case (*b*), the theory makes definite predictions about the dependence of D on the properties of the fluids, viz. its viscosity μ and its density ρ. (These two quantities have been assumed as identical in the two mixing fluids). No experiments to test this are as yet available. A similar situation exists regarding the lateral dispersion of, say, a fine stream of a miscible phase that would be injected into an otherwise homogeneous flow system contained in a porous medium. Therefore, although the above-mentioned linear experiments lend considerable support to the writer's statistical model of flow through porous media, some surprises might yet be encountered. In view of the simplicity of some of the features of the model, this should not be too unexpected.

In conclusion, the writer wishes to acknowledge that it was stimulating discussions with Dr. Todd which caused him to see the intrinsic connection between his own investigations, those of Day and those of Rifai; which, taken together, yielded the outlined edifice of a theory of flow of miscible phases in porous media. The writer is also indebted for advance copies of papers by Dr. Day and Mr Rifai.

REFERENCES

P. R. DAY (1956) : *Trans. Amer. Geophys. Un. 37*, 595.

M. N. E. RIFAI et al. (1956): «Dispersion Phenomena in Laminar Flow Through Porous Media». San. Eng. Res. Lab., University of California, Berkeley, Report I. E. R. Series No. 93, issue No. 2.

A. E. SCHEIDEGGER (1954): *J. Appl. Phys. 25*, 994; (1955): *Geofis. Pura Appl. 30*, 17; (1957): «The Physics of Flow Through Porous Media», University of Toronto Press.

G. I. TAYLOR (1954): *Proc. Roy. Soc.* A*223*, 446.

D. U. VON ROSENBERG (1956) : *A. I. Ch. E. Journal 2*, 55.

K. YUHARA (1954): *Geophysics* (Kyoto Univ.) *9*, 127.

THE USE OF RADIOACTIVE TRACERS IN HYDROLOGIC FIELD STUDIES OF GROUND-WATER MOTION (*)

HERBERT E. SKIBITZKE (**)
Mathematician
U. S. Geological Survey, Ground Water Branch, Phoenix, Arizona

Summary

The use of radioactive tracers to determine the direction and rate of ground-water motion is often suggested as a substitute for regional ground-water studies based on geologic analysis. The present writer concludes that the direction and rate of ground-water flow generally remain indeterminate. Further, almost without exception, knowledge of direction and rate of flow by itself does not constitute a solution to problems of ground-water flow. These findings are supported by an analysis of the principles of hydraulics of ground-water flow. Hydrologic field studies will continue to depend upon geologic studies of structure, stratigraphy, and rock type.

Introduction

The use of tracers as an investigative method is often considered in planning regional ground-water studies. The tracer experiments proposed or used for such studies generally involve the injection of water, or a similar liquid miscible with water, containing a readily identifiable compound in solution, into an aquifer through an injection well. The method of determining the pattern of flow of the tracer away from the injection well is through periodic sampling of nearby observation wells. The distribution of the tracer, that is, its location with respect to the position of the injection well and time, is considered to yield a basis for defining the hydrologic properties of the aquifer. Thus it would seem that the use of tracers would be a direct approach to the problem of obtaining a definition of the hydrology of ground-water systems. In this paper, the salient inter-relationships (for such an application of tracers) among ground-water hydraulics, tracer movement, and tracer detection is discussed in some detail.

Equations of Ground-Water Flow

Much has been written concerning the forces exerted on water moving within a porous solid. A practical equation of motion was derived from experiments conducted by a French engineer, Henry Darcy, during the middle of the last century. He showed, by experiments on sand filters through which liquids moved in one-dimensional laminar flow, that the general physical law relating frictional opposition to motion as being proportionel to the first derivative of motion, i.e. the velocity, also applied to liquids flowing in porous media. Since Darcy's time the results of his experiment have been extrapolated or extended. Darcy's experiments, with their implications, are discussed in a recent paper by M. King Hubbert (1956) who relates by analytical methods various extensions of Darcy's law to Newton's laws.

(*) Publication authorized by the Director, U. S. Geological Survey.
(**) Mathematician, Ground Water Branch, U. S. Geological Survey, Phoenix, Ariz.

Darcy's experiments led to the conclusion that, in essence the velocity of a liquid flowing in a porous medium varies as the difference in head with distance, i.e.,

$$V \alpha \frac{dh}{ds} \tag{1}$$

V = velocity
h = hydraulic head
s = distance

Later developments in the study of flow through porous media led to the following:

$$\vec{V} = -K \text{ grad } h \tag{2}$$

Equation 2 is the most commonly used form of Darcy's law.

The application of tracers to ground-water problems, requires a means for analyzing flow systems in which permeability varys in space. Thus it is necessary to extend Darcy's law to the condition in which permeability is a function of space. Extensions from Darcy's equation for the latter case are without physical verification, however they may be made in a manner similar to those for other dissipative fields such as electrical current flow in a resistive medium.

The differential equations of water flow through anisotropic media may be shown to be mathematically similar to those derived for heat flow. These latter equations are given, for example, by Carslaw and Jaeger (1947). The velocity component in the x direction for this case may be written as:

$$V_x = K_{11}\frac{\partial h}{\partial x} + K_{12}\frac{\partial h}{\partial y} + K_{13}\frac{\partial h}{\partial z} \tag{3}$$

where, for the flow of ground water,

K_{11} = the permeability in the x direction for the component of the hydraulic gradient in the x direction
K_{12} = the permeability in the x direction for the component of the hydraulic gradient for the y direction
K_{13} = the permeability in the x direction for the component of the hydraulic gradient in the z direction

Similar expressions for the components of the velocity in the remaining directions are:

$$V_y = K_{21}\frac{\partial h}{\partial x} + K_{22}\frac{\partial h}{\partial y} + K_{23}\frac{\partial h}{\partial z} \tag{4}$$

$$V_z = K_{31}\frac{\partial h}{\partial x} + K_{32}\frac{\partial h}{\partial y} + K_{33}\frac{\partial h}{\partial z} \tag{5}$$

Equation (3), (4), and (5) are components of the velocity vector $\vec{V}$ which is defined as:

$$\begin{aligned}\vec{V} = \vec{i}&\left[K_{11}\frac{\partial h}{\partial x} + K_{12}\frac{\partial h}{\partial y} + K_{13}\frac{\partial h}{\partial z}\right]\\ + \vec{j}&\left[K_{21}\frac{\partial h}{\partial x} + K_{22}\frac{\partial y}{\partial y} + K_{23}\frac{\partial h}{\partial z}\right]\\ + \vec{k}&\left[K_{31}\frac{\partial h}{\partial x} + K_{32}\frac{\partial y}{\partial y} + K_{33}\frac{\partial h}{\partial z}\right]\end{aligned} \tag{6}$$

in which $\vec{i}$, $\vec{j}$, and $\vec{k}$ are unit vectors.

The relation between $\vec{V}$ of equation (6) and grad h of equation (2) have been discussed by several authors, for example, Carslaw and Jaeger (1947). The feature of particular importance to the application of tracers is that the direction of flow in anisotropic media expressed by equation (6), is not everywhere parallel to the hydraulic gradient. Nearly all sediments are anisotropic to some degree, and the velocity field is therefore defined by equation (6). Most aquifers are nonhomogeneous and the manner in which permeability changes accordingly affects the flow pattern. Thus, equation (6) must be employed in conjunction with equations that define the aquifer nonhomogeneity if the flow field is to be described accurately. For the usual ground-water investigation, such a complex representation of the aquifer may not be warranted, however, it will be apparent from examining the relation between practical field use of tracers and the aquifer hydrologic characteristics that such detail is necessary in the use of tracers.

Width of the Tracer Stream in Homogeneous Media

The success of tracer tests in ground-water investigations depends largely on the success with which the tracer movement can be charted by observation from the surface. Normally, movement of the tracer is determined by periodic sampling in wells downstream from an injection point. The success of this method depends on locating the observation wells in such a way as to assure passage of the tracer through the observation well or wells. A study of the flow paths taken by a tracer fluid in an aquifer may yield a better understanding of the difficulties to be expected in selecting the locations of observation wells.

The effect of a continuous injection of liquid, with properties like that of water, through a well into an isotropic homogeneous aquifer in which the regional flow pattern prior to injection of the tracer is assumed to be one-dimensional is shown in

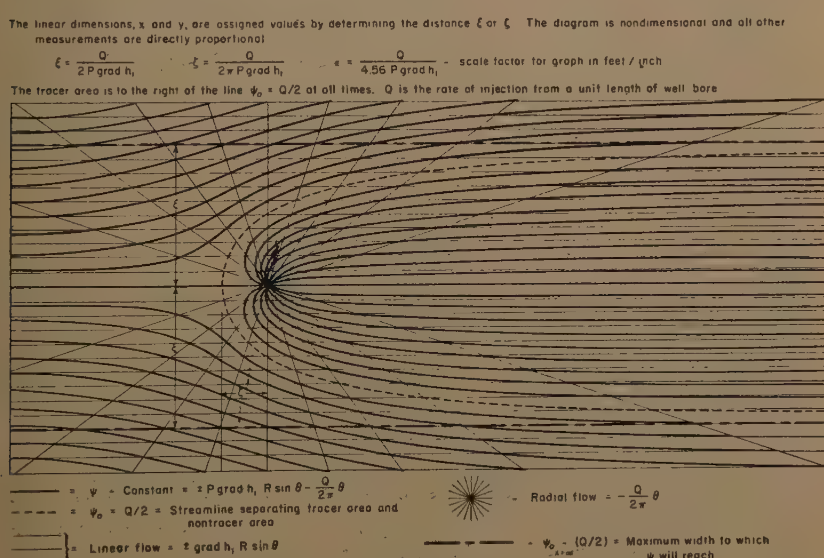


Fig. 1

figure 1. The increment of flow caused by the injected tracer is described by streamlines directed radially away from the well, the flow velocity being inversely proportional to the radial distance from the well. The flow of the two systems, linear and radial, superimposed create a velocity field which is a combination of the linear and radial flow systems. The equations for the flow lines of the combined field have been calculated by many authors; for example, Schlichter, 1899 and Milne-Thomson, 1949. From the mathematical development the width of the tracer path can be related to the injection rate and regional hydraulic gradient. This relationship is given by the following equation:

$$2\zeta = \frac{Q}{p \text{ grad } h_1} \tag{7}$$

Where

2ζ = maximum width of tracer band

grad h_1 = regional hydraulic gradient before injection occurs

P = aquifer permeability for a unit area

Q = rate of injection through a unit length of the well bore.

As an example, assume that 200 gallons per day of tracer-bearing water are injected at a constant and uniform rate per foot of aquifer thickness. Assuming the aquifer permeability is 1,000 gallons per day per square foot, and the regional hydraulic gradient is 100 feet per mile, the tracer band would spread to a maximum width of about 100 feet. To obtain such a width in a 100-foot thick aquifer would require an injection rate of 20,000 gallons per day. The permeability used here is representative of many aquifers composed of sand and gravel.

Equation (7) shows that the width of the tracer band is directly proportional to the injection rate; this is of considerable importance in tracer studies. If the aquifer contains water moving at comparatively high velocity under regional influences the tracer will travel a comparatively long distance in a short time but will occupy only a narrow segment of the flow field. Consequently to intercept the tracer the observation wells must be located precisely in accordance with a detailed knowledge of the regional flow direction or the narrow tracer band may not pass through the observation wells.

Injection of a small amount of tracer in a well causes a negligible head increase at the well in most aquifers and ground-water motion across the well bore, in effect, rinses out the tracer. This is usually the manner of injection for low concentration injection systems such as is employed when using radioactive tracers. The streamlines for this case are shown as dashed lines on figure 2, and can be computed by the expression

$$\psi = U\left(R + \frac{a^2}{R}\right)\cos\theta \tag{8}$$

Where

U = P grad h = the quantity of ground water flowing through a unit width of aquifer outside of the region disturbed by the well

R = $\frac{x}{\cos\theta}$ radial distance at which the streamline is located for a given angle θ

a = radius of the well.

The streamlines most widely separated but still traversing the well bore will include between them the area encroached by the tracer. These lines pass through the points R = a, $\theta = 0$ and $\theta = 180^0$. Substitution of these values in equation (8) yields

$$\psi = U(2a) \tag{9}$$

Equation (9) shows that the maximum width of the tracer band downstream from the injection well will be only twice the width of the well bore. In the development of

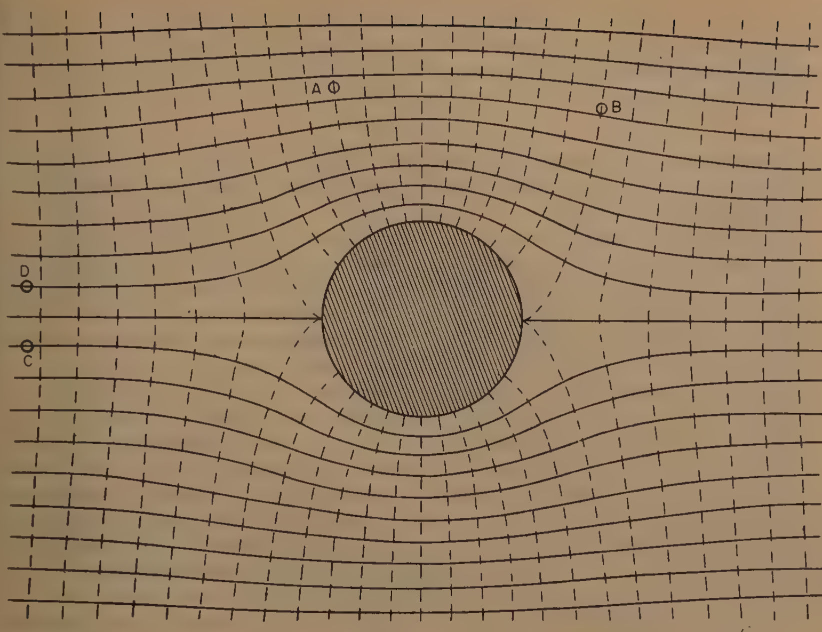


Figure 2. — Diagram showing the effect of a circular area of greatly contrasting permeability in a planar flow-net pattern (— — Flow lines when circular area has infinite permeability. — Flow lines when circular area has no permeability).

equations (8) and (9) it is assumed that the well is open, and that there are no losses caused by flow through a screen or casing perforations. If these losses are significant, the width of the contaminated band will be less than indicated by equation (9). Under these conditions, if the well diameter is of the order of one foot, the width of the tracer band will not exceed two feet in width, assuming that diffusional mechanisms are negligible.

Flow Paths in Nonhomogeneous Aquifers

The permeability of rock material comprising typical aquifers range through many magnitudes. The aquifers in the Basin Range province in southwestern United States, for example, are composed of sand and gravel interbedded with clay and silt. The permeability of the clay may be less than 2×10^{-4} gallons per day per square foot, whereas the permeability of the gravel may be greater than 10^5 gallons per day per square foot (Wenzel, 1942), a range of variation of 10^9. This variation occurs as a general feature in most aquifers. Permeabilities in hardrock aquifers, such as in the basalts of the Snake River Plain in northwestern United States, probably are in even greater contrast. These figures illustrate the great differences in permeability of water-bearing material that normally occur in aquifers even over comparatively short distances.

For the purposes of this paper the nonhomogeneity resulting from these differences can be considered, from an analytic standpoint, as forming an idealized system. By such idealization a few selected cases may be considered in order to obtain a concept of the effect of nonhomogeneity on the direction of flow. Assume that the aquifer

has a certain uniform permeability with selected zones within the aquifer of either infinite or zero permeability ; also assume for simplicity that the aquifer is isotropic. For steady flow under these conditions, the equation can be reduced to the Laplace of continuity equation:

$$\Delta^2 h = 0 \tag{10}$$

Equation (10) may be solved for all boundary conditions found in physical problems. The solutions however must often be by approximation methods, and for many cases may be difficult to obtain.

The illustration of the effects on flow in nonhomogeneous aquifers are simplified by studying only flow in a single plane. This may be accomplished by finding solutions to equation (10), for geometrical configurations of interest in two dimensions. Several such solutions are shown in figures 2 to 5. The illustrations show streamlines in the vicinity of areas of high or low permeability. The effect of the shape of the area on the streamline configuration is indicated by direct comparison.

In figure 2 the dashed lines indicate the direction of flow of ground water in the vicinity of a circular area of infinite permeability, for example, through an open well bore. If the circular area were entirely sealed, i.e. of zero permeability and the general direction of flow was shifted 90 degrees, the streamlines would be as indicated by the solid lines. Figure 3 illustrates the streamlines in the vicinity of an elliptical area of high or low permeability; figure 4 the streamlines in the vicinity of a narrow rectangular area; and figure 5 the streamlines in the vicinity of an irregularly-shaped area. The figures are nondimensional and could represent conditions within a few feet of a well bore, or regions encompassing many square miles of area.

It can be inferred from figures 2 to 5 that the flow in a nonhomogeneous medium is distorted both as to direction and velocity, in comparison with the flow configuration in a homogeneous medium. Over comparatively large distances in nonhomogeneous

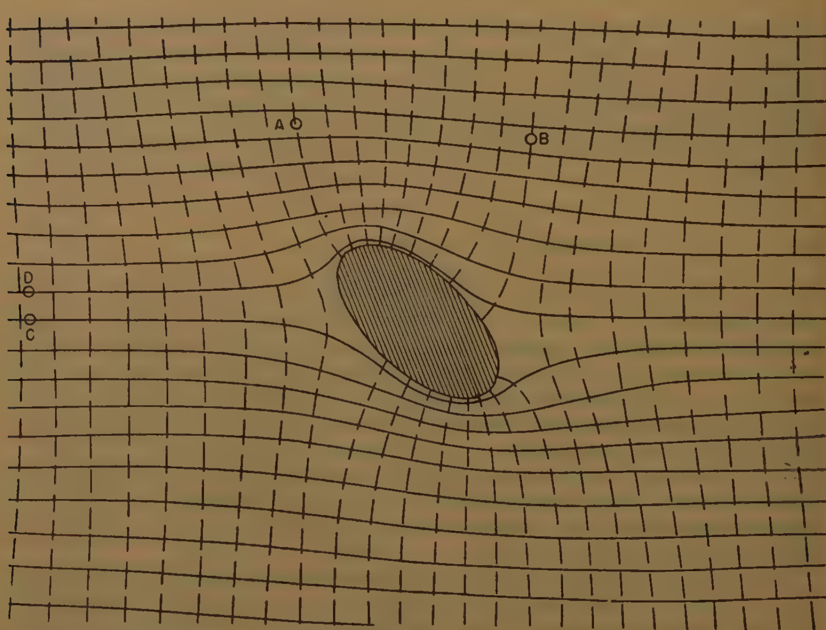


Fig. 3

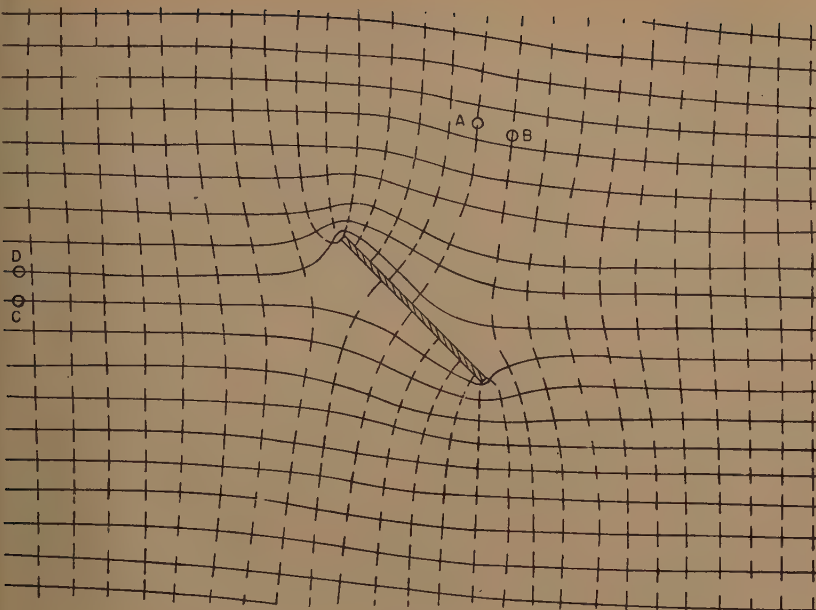


Fig. 4

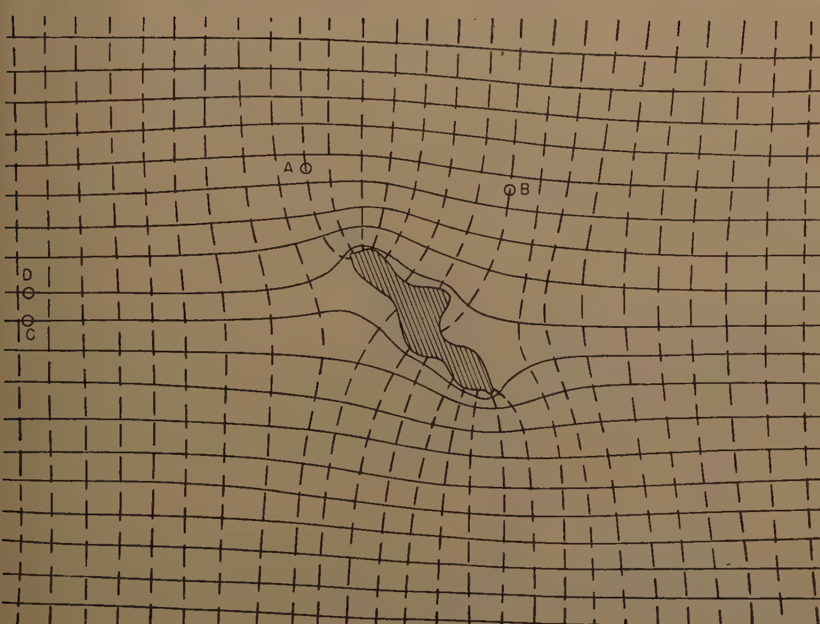
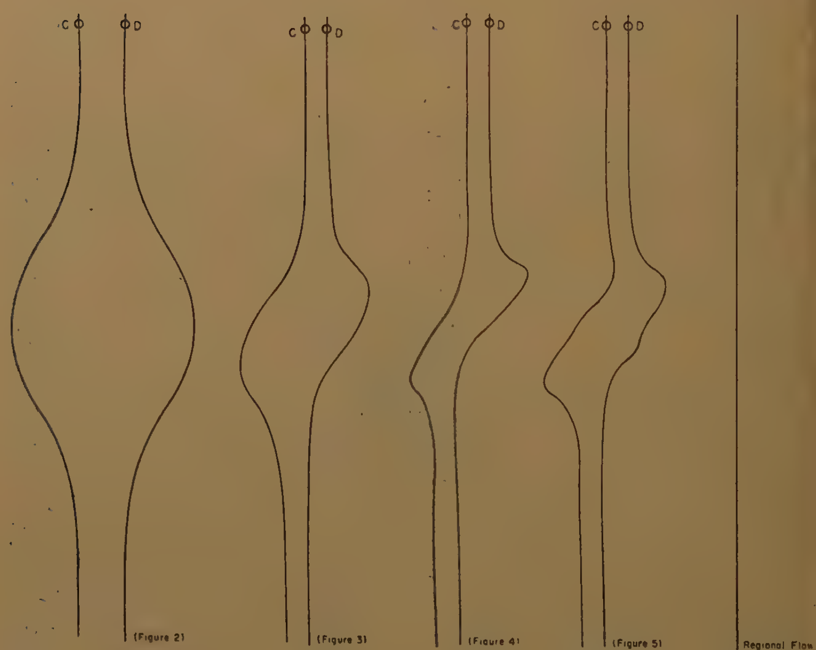


Fig. 5

Note A, B. - Reference points (See Figs 2-5)

Fig. 6



Note: C, D, — Reference points (See Figs 2-5)

Fig. 7

media local nonhomogeneity becomes important only as part of an average and the regional flow system appears grossly to be more nearly like the ideal homogeneous system. Locally however the direction that the tracer would take, for example in leaving the well bore, is dependent upon the distribution of permeability. The dependence of flow direction on permeability distribution is qualitatively apparent from figures 6 and 7. On figure 6 selected streamlines are shown for the conditions of areas of comparatively high permeability, shown on figures 2 to 5. Correspondingly, figure 7 is for the areas of low permeability.

The ground-water velocity would be affected similarly by the presence of areas of high or low permeability in the vicinity of a tracer. An example is shown in figure 8 which is taken from the flow system of figure 2. The circular area is assumed to be of high permeability; selected streamlines and the direction of flow are shown. At

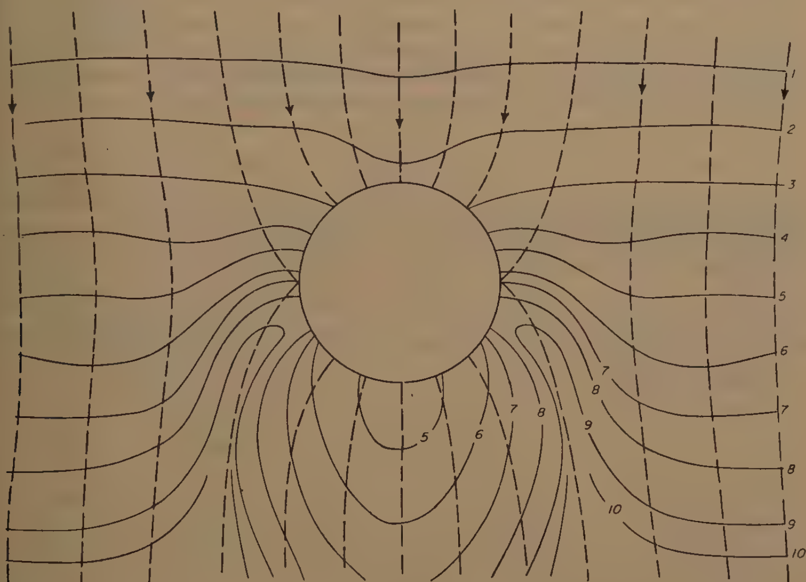


Fig. 8

some reference time, $t = 0$, it is assumed that the tracer front is normal to the direction of flow. As it advances toward the area of high permeability, higher velocities there cause a more rapid advance and the tracer front is distorted. An indication of the variation in velocity between points on any of the streamlines near or spanning the circular area can be obtained by inspection.

Conclusions

The knowledge, even in detail, of the direction or velocity of flow of ground water is not especially significant in solving most of the problems connected with ground-water exploration or development. There are, however, certain problems in ground-water hydrology, particularly those connected with waste disposal, in which

knowledge of the direction and rate of flow would be helpful in their solution. Although the use of tracers would appear to be a direct and reliable method for determining the regional direction and rate of flow there are several factors which would seem to limit their effectiveness and application.

Inasmuch as ground-water velocities are generally very low the observation wells installed to intercept the tracer generally must be located within about 500 feet of the injection well so that the tracer test does not require an excessive amount of time. In contrast, however, the width or length of regions of interest in most ground-water studies is of the order of several miles. Hence for practical and perhaps economical reasons the tracer test can generally involve only a small part of the ground-water flow systems. Considering this dimensional restriction and the pronounced effects on flow direction and velocity caused by the nonhomogeneous and anisotropic character of most water-bearing formations, it seems likely that tracers tests alone will rarely provide a reliable indication of regional direction and rate of ground-water flow. Consequently it appears that in general the value of tracers in ground-water hydrology will remain essentially a method useful in laboratory experiments, whereas the definition of ground-water characteristics of significantly large areas will continue to dpend on detailed regional geologic and hydrologic studies.

REFERENCES

Hubbert, M. King, *Darcy's Law and the Field Equations of the Flow of Underground Fluids*, Jour. Petrol. Technology, T. P. 4352, Oct. 1956.

Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Oxford Press, 1947.

Milne-Thomson, L. M., *Theoretical Hydrodynamics*, McMillan Press, New York. 1949.

Slichter, C. S. U. S. Geological Survey Nineteenth Annual Report, Part II, p. 295-384. 1899.

Wenzel, L. K., *Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods.* U. S.Geol. Survey Water-Supply Paper 884, 1942.

LAWS OF FORMATION OF UNDERGROUND RUN-OFF INTO OPEN RESERVOIRS AND RIVERS AND METHODS OF DETERMINATION

F. A. MAKARENKO

1. In the water balance equation of the Earth and of separate territories the underground run-off has no definite quantitative characteristics.

2. The underground run-off has a group texture in its regime, in chemical composition, in energy of geological activity; its zonal structure is caused by bases of the run-off drainage.

3. Recently new methods of calculation of the underground run-off into water systems and basins, taking into consideration its regime, zonal structure and hydrochemistry, have been worked out in the USSR. Among them there are a hydrochemical method of A. T. Ivanov and hydrogeological methods of F. A. Makarenko and B. I. Kudelin for waters hydraulically not connected but linked with rivers and open basins. These methods make it possible to directly compute hydrographs of the underground run-off.

4. In the forties of this century when there was a level drop of the Caspian Sea and it was necessary to study its water balance, the Laboratory of Hydrogeological Problems of the Academy of Sciences of the USSR made a special investigation of the underground run-off into this basin.

The author has defined and mapped four genetic groups of the underground run-off into the Caspian Sea:

1) underground soil and deep waters coming to the sea through river drain, i. e. those discharging on land;

2) ground waters of the upper run-off zone coming ot the sea directly from a narrow land band along the sea perimeter;

3) deep underground waters discharging directly into the sea from shores and the sea bottom;

4) underground alluvial waters flowing into the sea from the river mouth.

River waters flowing into the sea contain 50% and more of underground water most of the ground run-off origin. A total of the direct underground run-off into the sea was found to be about 5 km^3 per year. A part of the deep nourishment considerable in the zone of Alpine disturbances along the Apsheronsky peninsula — Cheleken direction is not more than several per cent of this figure.

5. An interesting investigation was made by the author of water and chemical underground nourishment of the dried Uzboi River in Kara-Kums. The final computation were based on the balance method and on modulating water and chemical run-off into the Uzboi River within its bed. The calculations show that an influx of mineral waters into the Uzboi River per second was, with temporary surface waters, 1.3 m^3, with ground waters —2.7 m^3, with deep pressure waters —0.05 m^3 and respectively, an influx of salts was: 4.54 and 5 kg per sec. It was established that the modern aquiferous and hydrochemical regimen of the Uzboi River, with its accumulation of salts in a solid phase and saline lakes, chiefly consists of waters of the ground run-off. Besides, a geologo-hystorical analysis of this phenomenon enabled us to show in figures an extremely important role of the aeolian factor in a continuous outwash of salts from the bed of the Uzboi River.

STUDIES ON THE GROUNDWATER CONDITIONS OF THE MAHENDRAGARH DISTRICT, PUNJAB (INDIA)

G. C. CHATERJI & A. B. BISWAS
Geological Survey of India, Calcutta

ABSTRACT

Mahendragarh district is a semi-arid tract lying in the south-western part of the Punjab State. It consists of fairly level to gently undulating alluvial and sandy plains, interspersed by sand dunes, isolated hillocks and ridges. The Recent and Sub-Recent alluvial formations underlie more than 98% of the area. The rest of the area is occupied by hard formations belonging to the Delhi System of rocks which are classifiable into the Ajabgarh Series and Alwar Series in order of antiquity.

Rainfall with an annual average of 16 to 18 inches forms the chief source of recharge to the groundwater reservoir within the alluvium consisting of a succession of clay with *Kankar*, loam, silt and sand. The thickness of alluvium is variable from place to place. In the northern part of the district it is not less than 341 feet, but in the southern part it gradually thins down to a depth of 60 feet below land surface.

Depth to water generally ranges from 50 to 100 feet below the land surface in the eastern side of the central ridges and also in the northern part of the area. Beyond the western face of the central ridges groundwater often occurs at a depth of 200 feet or more below land surface. This indicates that the rocky ridges form a barrier to the groundwater movement.

Shallow groundwater from the eastern part is of sodium-bicarbonate type while the same from beyond the western face of the central ridges is of normal calcium-bicarbonate type. Quality of groundwater is generally better in the western parts with chloride contents usually below 200 ppm. Groundwater in the extreme northern and east central parts is highly mineralised and is characterised by very high concentration of chloride and total hardness-causing ions which may be anything between 4,000 to 8,000 ppm.

1. INTRODUCTION

The paper presents the results of the studies of the groundwater resources of the Mahendragrah district occurring in the south-western part of the Punjab State (India). The area investigated includes parts of the Mahendragarh and the Dadri tahsils of the district lying between latitudes 28°05' and 28°45' and longitudes 76°00' and 76°30' on one inch to one mile Survey of India topographical sheet No.53D/3 and parts of sheet Nos. 53D/2, 53D/4, 53D/6, 53D/7 and 53D/8 and measures about 800 square miles in areal extent (please see plate No. 1). Field studies in this area were carried out between February, 1954 and July, 1956 with occasional breaks during monsoons. The investigation deals mainly with the occurrence of groundwater in the Mahendragarh region in relation to its regional geology laying special emphasis on its geo-chemical aspects.

2. PREVIOUS LITERATURE

There is no published record available of any type of previous work done on the groundwater geology of the Mahendragarh district.

The area has, however, attracted the attention of earlier geologists from time to time. Although references to the occurrence of the celebrated Flexible Sandstone or Itacolumite in the Kaliana Hills, (28°33'10" : 76°11'58" ; 53D/2) area vailable

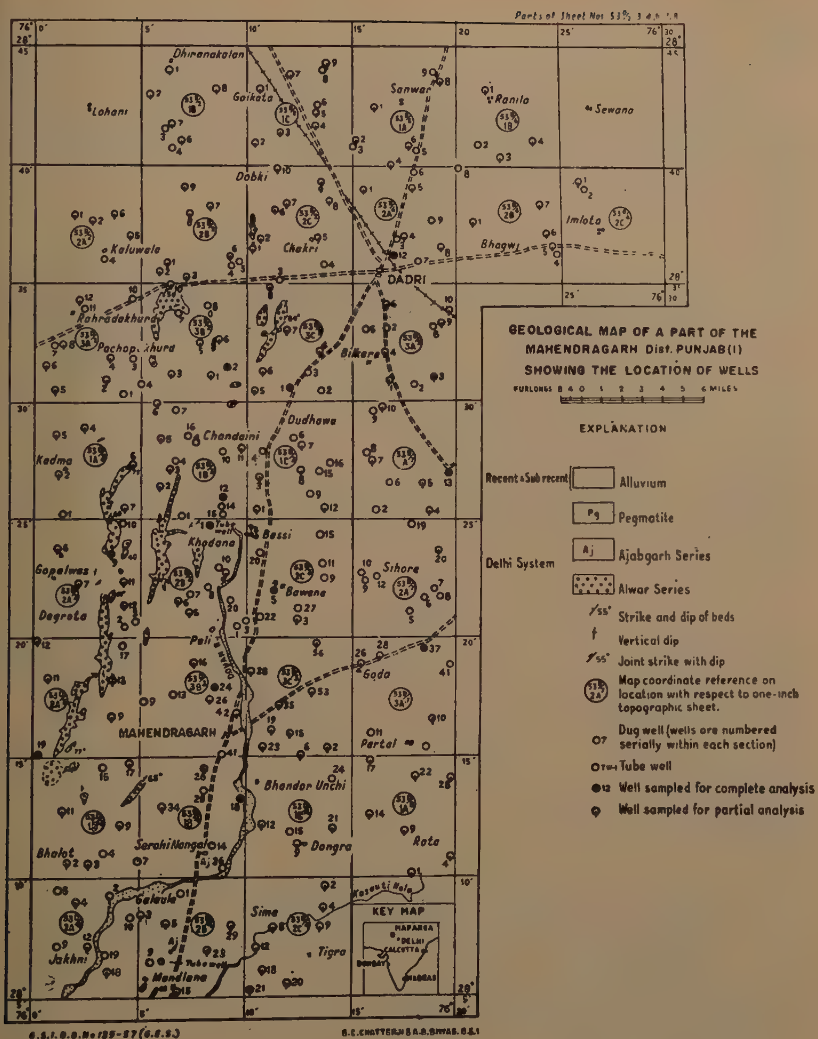


Plate I

in earlier literature (Medlicott: 1874, Oldham: 1889), Hacket (1881) appears to be the first geologist to visit the district in the early eighties of the last century and describe the quartzites occurring in the Kaliana hills which he referred to the Alwar Series of the Delhi System.

Bose (1906) also later on paid a visit to the area around Narnaul (28°02'30" : 76°06'30"; 53D/4) and described the granitoid gneisses and quartzites occurring there.

Systematic geological mapping of the district was started by Raina in the 1950-51 field season.

3. CLIMATE

Seasons:

The climate of the region is semi-arid with a long dry hot weather period. The cold season generally sets in towards the end of October. By the end of February or the beginning of March the temperature goes up. The summer continues through April, May and June. The rainy season begins in July and often continues upto the first half of September. Hot, dustraising winds are common in April, May and June.

Rainfall:

At Narnaul (28°02'30" : 76°06'30"; 53D/4) the mean annual rainfall (based on a 25 year record between 1929 and 1953) is 18.58 inches. Marked departures from the mean occur rather frequently. At Dadri (28°35'23" : 76°16'15"; 53D/6) the average annual rainfall for the 12 year period from 1940-1951 is 15.97 inches. For Mahendragarh (28°16' : 76°09'; 53D/3) records are available only for four years which show a maximum rainfall of 20.05 inches in 1953 and a minimum of 10.45 inches in 1951, the average being 15.67 inches.

Precipitation in this area varies greatly from year to year. The areal distribution and intensity of rainfall during a given season also vary within short distances. Such vagaries of rainfall had led to recurrent famines in the past.

Evaporation

No evaporation records are available for the area under consideration. However, average annual evaporation in the Delhi region (about 70 miles east of the area) is about 100 inches; and the same is of the order of 120 inches at Bikaner (a little over 200 mile WSW of the area). So it may be presumed that the average annual evaporation for the area lies between these two figures.

4. PHYSIOGRAPHIC FEATURES

Topography

This semi-arid tract is akin to Rajasthan in its physiographic features. It consists of fairly level to gently undulating alluvial and sandy plains interspersed by sand dunes isolated hillocks and rocky ridges. A series of long ridges which forms a sort of chain along the west central part of the area is the most striking landmark of this region. Starting from Sohla in the south-western corner of the area, these ridges run in a north-north-easterly direction for about 16 miles upto Main.

A stretch of alluvium, soil and blown-sand intervenes between these ridges and the hills of Siswala and Kaliana in the north. The crests of the ridges generally range in elevation from 1250 feet to 1700 feet above the mean-sea-level. The peak of the Khodana hill (Δ 1720') in the central part forms the highest point in the area under investigation. The country slopes down either way from this belt of ridges; but plains to the west stand at higher elevation than those on the east.

Besides, there are also a few isolated and widely separated hills on either side of the Narnaul-Mahendragarh-Dadri road. Blown sands are often seen to have gathered along the slopes of the ridges and hills to a fairly good height; and sometimes the slopes are covered by talus.

The south earstern, eastern and northern parts of the area are essentially plains with scattered sand dunes. The dunes are, however, more concentrated in the

south-east, east-central and extreme north-western corners of the area. The western and north-western parts are more or less sandy tracts where sand dunes are very conspicuous. The most prominent series of sand dunes cuts across the northern part of the area in a E-W direction. Another cluster of sand dunes occurs in the south-eastern part of the area. The central part is more or less a plain country with only a few scattered dunes. The dunes, like the hills and ridges of the region, are usually bare of vegetation. The elevations of the plains above the mean-sealevel range from 901 to 981 feet in the south, 723 to 889 feet in the north, 842 to 981 feet in the west and from 728 to 901 feet in the east. The country along the eastern part of the area which is fairly level, has an average gradient of roughly 7 to 8 feet per mile from south to north. Similarly the average slope from west to east ranges roughly from 3 to 5 feet per mile. In other parts the gradients are not very uniform due to occasional interference by sand dunes, hills and ridges. The master slope of the country is from south to north, although the plains also slope from west to east.

Drainage:

The region has no effective drainage system. The Dohan, an ephemeral stream having a fairly wide and sandy channel, rises in the Jaipore hills about 40 miles SSW of Mahendragarh and travels in a north-north-easterly direction before it enters the area under report. Then onwards the stream runs more or less in a northerly direction till it gets lost in the sands about half-a-mile west of Bassi in the Central part of the area. The stream carries water in the Mahendragarh area only during the heaviest rains. *Nalas* emerging from the hills and ridges also bring in some water into the plains during the monsoon.

5. Geology

The occurrence, origin, quality and availability of groundwater in the Mahendragarh district are related to the Recent and Sub-Recent formations. Because geological formations of earlier age do not contain groundwater in substantial quantity in the region studied they have been treated in a rather general way in this paper.

The hard rock formations which occur in the area belong to the Delhi System. The general succession of the Delhi System as established by Heron (1917) in the type area in Rajasthan is tabulated below:

Recent and Sub-Recent-Soil alluvium, blown sand and *Kankar*

Delhi System (Algonkian)	Intrusives: Pegmatites, Quartz-veins, granites and amphibolites.	Ajabgarh Series	Slates, phyllites, mica-schists, quartzitic sandstones and impure limestone.
		Hornstone-breccia	
		Kusalgarh-limestone	
		Alwar Series	Quartzites, Arkose, grits, conglomerates, limestones, micaschists and contemporaneous volcanic rocks.

The two middle members, Hornstone-breccia and Kusalgarh limestone, do not crop-out in the area investigated. The Ajabgarhs occur in the southern part in a few detached hills. The rest of the hard rock formations which crop-out prominently in the hills and ridges of the area belong to the Alwars. The strata are highly disturbed. Minor anticlines and synclines have often been noted locally. The rocks are characterised by high dips often approaching verticality. The strike is, however, fairly steady varying between NNE-SSW and S-W. The general dip is between 55 and 80 degrees, the direction varying between WNW-ESE and W or E.

Alwar Series:

The rocks belonging to the Alwar Series are mainly represented by very hard and compact quartzites with occasional bands of phyllites and mica-schists.

The quartzites are usually grey or pale pinkish in colour with shades of buff and white and are more or less streaked. They are generally vitreous, breaking with sub-conchoidal fractures and with sharp and splintery edges. Extensive exposures of quartzites are found to occur in the hills and ridges around Sohla, at Rajawas, Khodana, Kaliana, Siswala and Manakawas. The quartzites are sometimes felspathic, micaceous or calcareous. The Alwar quartzites are highly jointed. Three sets of joints striking NNE-SSW, NNW-SSE and E-W and dipping at various angles from 0 to 90 degrees are seen to have been well developed. The rocks are often characterised by the occurrences of ripple marks, current bedding and lamination.

Ajabgarh Series:

The Ajabgarh are mainly confined to the southern-most part of the area in a few detached out-crops. They consist dominently of argillaceous and calcareous materials represented in this area by mica-schists and calc-silicate rocks. Subordinate amount of quartzites or quartzitic sandstones also occur. Slates and phyllites are the commonest rock types in the typical Ajabgarh out-crops; but such rocks do not occur in the area studied. Schists and calc-silicates representing the Ajabgarhs are found to occur in the hillocks at Sirohi-Nangal, Gulaula, Dhani-Faizabad, Baskararod and Jakhni.

Quartzite members of the Ajabgarh Series are generally dark grey or reddish in colour, and are not so vitreous nor so compact as the quartzites belonging to the Alwar Series. Joints are also common in the Ajabgarh rocks, but are rather irregular. The Ajabgarhs being mostly composed of soft argillaceous materials are easily liable to erosion and consequently tend to occur in irregular and isolated patches where structures are favourable for their preservation.

Intrusive rocks:

Igneous intrusives occurring in the area are represented by granite and pegmatities. Quartz-veins cutting across the bedding planes of the country rocks are quite common in the hills around Sohla, Baskhurd and Bassi and also in the Dhadeed hill ($<$ 1630'), about two miles west of Dadhor.

Fairly big intrusions of pegmatite containing large crystals of tourmaline and small books of mica occur in the hillock near Sirohi Nangal and Jakhni.

An interesting out-crop of graphic granite has been recorded to occur in the hillock near Bhankri. The granite is whitish in colour containing opalescent quartz in a felspathic matrix. Pegmatitic facies of the granite is found to have developed in the northern part of the hill.

Recent and Sub-Recent formations:

The Recent and Sub-Recent formations include both fresh water and sub-aerial deposits and occupy more than 98 per cent of the area investigated.

The alluvium, a fresh water deposit of the Indo-Gangetic river system, forms the most wide spread formation in the area. It consists of a succession of clay with *kankar*, loam, silt and sand.

Talus along the hill slopes and wind blown sands form the sub-aerial deposits. The talus does not extend to any appreciable distance outward from the foot of the hills. Wind blown sands carried in from sources outside of the area occur mantling the plains in patches of variable extent almost throughout the region; but they are more common in the west than else where. These wind blown sands are often heaped up into dunes which are usually 20 to 25 feet in height above the surrounding land surface. The dunes generally occur as ridge-like bodies mainly having an east-west trend.

Occasionally a subsidiary series of N-S trending dunes is also noticed.

The sands composing the dunes are very fine grained, well rounded and are very highly sorted by wind action. They are composed mainly of quartz and felspar. A few dune samples were analysed by Biswas (1956) for heavy minerals and the heavy mineral assemblage shows the presence of iron-ore minerals consisting of magnetite and ilmenite together with pyroxenes, amphiboles, garnet, epidote, zeisite, tourmaline, micas, staurolite, kyanite, sillimanite and apatite. Zircon and monazite have also been noted to occur in minor proportion.

In the Mahendragarh tahsil sandy loam and sand form the predominating soil while in the Dadri tahsil sandy soil with patches of loam prevail. Sandy soil is a very poor land, but it requires little ploughing, as it readily absorbs moisture. Sandy loam, which is easy to plough and at the same time retains moisture, is considered to be a good soil.

6. Groundwater

Rainfall is the chief source of groundwater which occurs in a fairly thick zone of saturation within the alluvium. The soft rock formations constituting the blown sands and the alluvial fill comprise materials of varying degrees of permeability. It has, however, been found that the blown sand deposits are generally, almost wholly devoid of any recoverable water. In the alluvium the water-table, representing the upper limit in the zone of saturation, rests at varying depths below the land surface. The materials above the water-table allow free passage of percolating water which replenish the groundwater reserves. Thus the groundwater body occurs as if impounded in a reservoir and the water-table is free to rise and fall as water is added or discharged. No evidence has been obtained of confined water (artesian) conditions.

The depth and slope of the water-table:

From an inventory of some 600 wells done in the area it is found that depth to water below land surface generally varies between 50 and 100 feet; but in the western parts particularly in the area to the west of the west-central ridges the depth to water is often 200 feet or more below land surface. The greatest measured depth to water in the area was 226 feet below ground surface in the well No. $53D/5\text{-}3A_{10}$ at Madhogarh. Water-table generally comes nearer to the surface from south to north and from west to east, and is sub-parallel to the slopes of the country.

In the southernmost parts water-level elevations with reference to the mean sea

level datum vary from roughly about 940 feet in well No. 53D/4-2A$_{18}$ at Gehli to about 858 feet in well No. 53D/4-2C$_{17}$ at Pattni. West of the west-central ridges water-level elevations range from roughly about 901 feet in well No. 53D/3-3A$_{18}$ over one mile west of the southern edge of the hill Δ 1631 feet to 802 feet in well No. 53D/3-1A$_1$ at Badrai; but in the area adjoining the west-central ridges to the east the same vary from about 831 feet in well No. 53D/3-3A$_6$, about a mile SSW of Dadhor, to 774 feet in well No. 53D/3-1B$_1$ at Naurangabad. This great differences in water-level elevations in adjacent parts appear to be due to the nearly north-south trending impermeable rocky ridges forming a barrier between the two regions thereby severing the west to east continuity of the groundwater body. However, the groundwater movement from south to north is maintained. In the easternmost parts elevations vary from above 846 feet in well No. 53D/8-1A$_8$ at Maholra to 611 feet in well No. 53D/6-1B$_1$ at Ranila. From the above it is found that the water-table has an average gradient of roughly about 7 to 8 feet per mile from south to north. The water-table gradient from west to east is, as pointed before, interrupted. In a generalised plot it is found to range at 3 to 4 feet per mile (west to east). The groundwater body attains a master slope in a northeasterly direction as the resultant of the above two gradients.

The water-table is reported to have gone down in many parts in the south which may be due to the deficiency in rainfall in recent years.

Source and disposal of groundwater:

As already mentioned rainfall is the chief source of groundwater. A part of the groundwater recharge is obtained from water directly penetrating downward to the water-table from the land surface within the confines of the area. Although absence of any effective drainage system and prevalence of loose sandy soil over large parts of the alluvial tract favour greater underground percolation, the high degree of evaporation somewhat offsets this advantage. The amount of replenishment is greatest in the year of above normal rainfall.

Groundwater moves down the slope of the watertable, the rate of movement depending principally on the hydraulic gradient and the permeability of the formations in the zone of saturation.

No groundwater is discharged naturally within the confines of the area, since the water-table occurs generally at least 50 feet below the land surface. Artificial discharge takes place by withdrawals from wells for irrigation and other purposes; but a part of the water used for irrigation again goes back to the water-table.

7. Geological formations and their Water Bearing properties

The areal extent of the different formations and the location of the wells examined are shown in plate No. 1. The alluvium lying under the superficial deposits (dunes, sands, soil, etc.) occupies roughly more than 98% of the total area examined. The hard rock area comprises roughly about 2% of the area. Superficial deposits lie above the water-table.

Water in the hard rock formations:

Not much is known about the occurrence of ground-water in the hard rock formations belonging to the Delhi System; because in and near the out-crop areas such rocks lie above the zone of saturation and where covered by alluvium they occur below the reach of the shallow sells. The hard rocks as such are impermeable in

nature. It is, however, likely that some water occurs along joints, cracks, fissures, cleavage planes and such other openings in the hard rocks underlying the alluvium below the zone of saturation.

In the south western part of the area some of the open wells are reported to have touched bed-rock consisting of such rock types as granite, amphibolites and mica-schists at depths varying from 60 to 115 feet below land surface. The relationship of these sub-surface hard-rocks with the out-cropping Delhi System of rocks is, however, not clear. The yield from such wells is found to be very meagre. The vertical extent of the decomposed zone of bed-rock below the zone of saturation and its water yielding capacity are not yet precisely known.

Water in alluvium:

In the area investigated groundwater is almost entirely tapped from wells dug in the alluvium. Since aquifers occur exclusively in the alluvium, information on its texture, mineral composition, thickness and structure and its areal continuity and facies changes are of immense value in its evaluation as a source of water supply. But in the present area the overall depth and the composition or spread of the strata constituting the alluvium is not precisely known. It is evident that the thickness of the alluvium is variable being less near the hard rock out-crops, but the depth of the alluvium is generally greater in the flat land away from the rocky areas.

From the logs of three bore-holes recently drilled in the Dadri tahsil it is found that the alluvium in those areas at least is not less than 341 feet in depth below ground surface; but the drillers' logs of the strata penetrated by those bore-holes suggest that they consist mainly of clay with occasional 'kankar, bands and very subordinate amounts of sand beyond a depth of about 70 feet below the land surface. In the extreme southern parts of the area, however, the alluvium is rather thin; it is only 60 feet in vertical thickness near the village Baskararod. A study of the logs of the three bore-holes in the Dadri tahsil suggests that the water yielding materials form only 19.7 per cent, 7.4 per cent and 2.4 per cent of the total depths penetrated by the bore-holes at Khodana, Dadri and Ramnagar respectively. Again, about half the amount of 19.7 per cent of the sand in the 218 feet bore-hole near Khodana is angular in nature, and as such appears to have been derived locally. The prevailing low yield of the shallow wells indicates that the near-surface deposits are ill-sorted in nature and have low permeability. It is reported that bore-holes put down below the bottom of existing dug-wells have sometimes increased the yield (e.g. Well No. 53D/3-2C_8 at Bawana, well No. 53D/2-3A_2 at Pachopa Kurd or Kubja); but instances are not few where even such bores failed to augment the yield (e.g. Well No. 53D/7-2A_1 at Kanina-Khas, Well No. 53D/4-1C_1 at Atali) or better the quality of the water (e.g. Well No. 53D/3-1C_{14} at Siyana and Well No. 53D/3-1C_2 at Palri).

Thus it is observed that the thickness and character of the water-bearing formations in the alluvium vary from place to place and within short distances. All these probably point to the fact that very thick and extensive occurrence of good water-bearing materials in this area is not very likely.

Water in the alluvium moves largely through interstitial openings or pores in the more pervious beds which lie between the water-table and the underlying bed rock. The sustained capacities of the existing shallow dug-wells used for irrigation range roughly from 5,000 to 34,000 gallons of water per day (working 10 hours a day); but a yield of about 70,000 gallons of water per day has also been locally noted (e.g. Well No. 53D/8-1A_9 at Maholra).

Groundwater in the Mahendragarh area is believed to have originated entirely from rain. As such all the changes in its quality as noted in the water samples collected from shallow dug-wells have occurred largely subsequent to its penetration into the aquifers. Study of the geo-chemistry of groundwater is of great value, as solution of some of the problems of its genesis and route of its movement may be possible of the basis of the analysis of the quality distribution patterns of groundwater.

Complete chemical analyses of 12 well water samples together with partial analyses of about 200 water samples collected from shallow, dug-wells spaced at regular

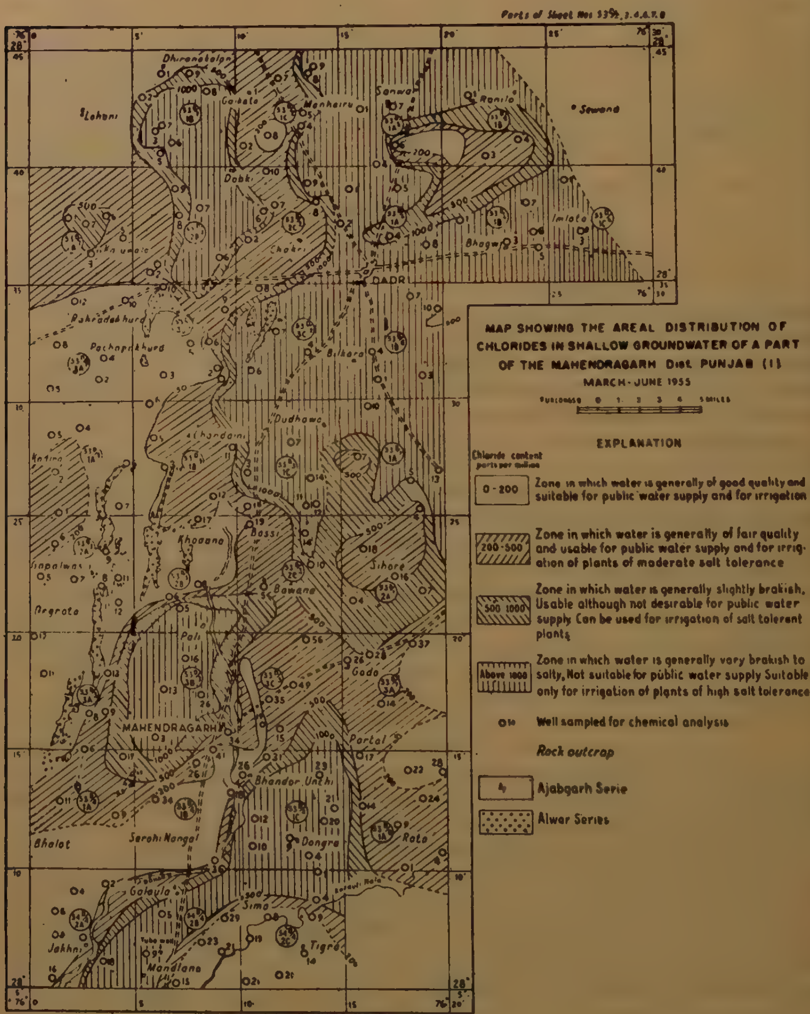


Plate II

intervals throughout the area, during March-May 1954, March-June, 1955 and December-July, 1956 reveal certain interesting geo-chemical peculiarities. The samples were analysed in the Headquarters Chemical Laboratory of Groundwater Exploration Section, Geological Survey of India by Messrs. B. K. Handa, S. R. Maitra and V. Kripakaran. To determine relationships in chemical character of the waters, use is made of a trilinear graph on which the analyses are plotted. The distribution of the analyses on the grid is a function of the chemical character. The grid, diamond shaped (see plate V) has scales for an-ions and cat-ions arranged along the edges, from 0 to 100 per cent reacting value. The grid can be sub-divided into 5 areas: area 1, spans the plottings of analyses in which carbonate hardness (secondary

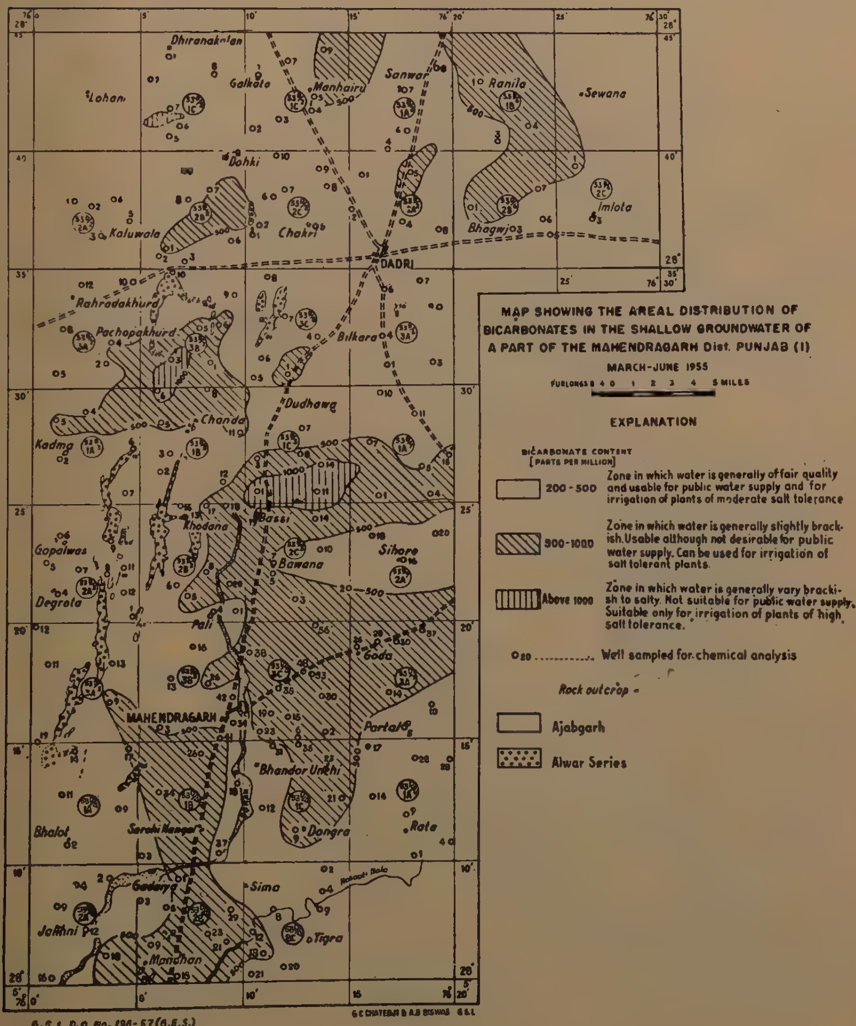


Plate III

alkalinity) exceeds 50 per cent of all dissolved solids in term of chemical equivalents; area 2, those in which carbonate-alkali (primary alkalinity) exceeds 50 per cent; area 3, those in which non-carbonate hardness (secondary salinity) exceeds 50 per cent; area 4, those in which non-carbonate alkali (primary salinity) exceeds 50 per cent; area 5, those in which no one of the preceeding four characteristics is as much as 50 per cent.

On plate V all the 12 complete analyses have been plotted. Their distribution shows the following general types based on the above generalisations:

1. A mass of 5 analyses in the lower part, all representing waters high in sodium and bi-carbonate (primary alkalinity).

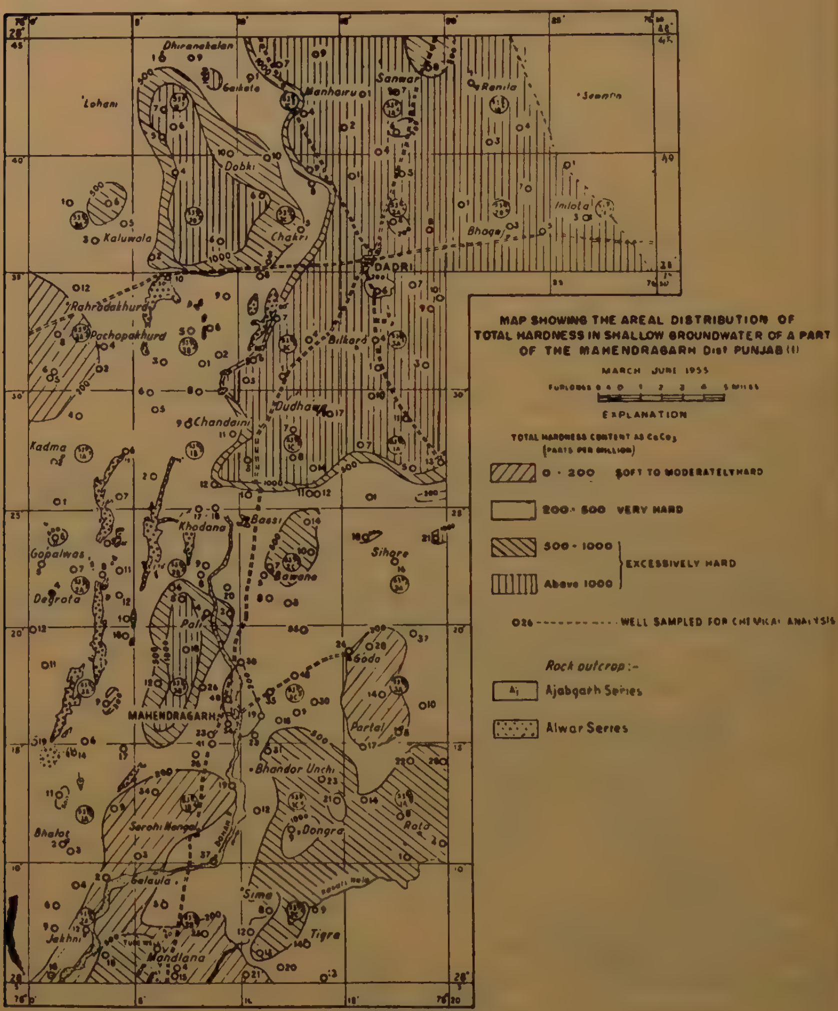


Plate IV

GRAPHICAL REPRESENTATION OF COMPLETE CHEMICAL ANALYSES OF 12 SAMPLES OF WELL WATERS FROM MAHENDRAGARH DIST PUNJAB(I)

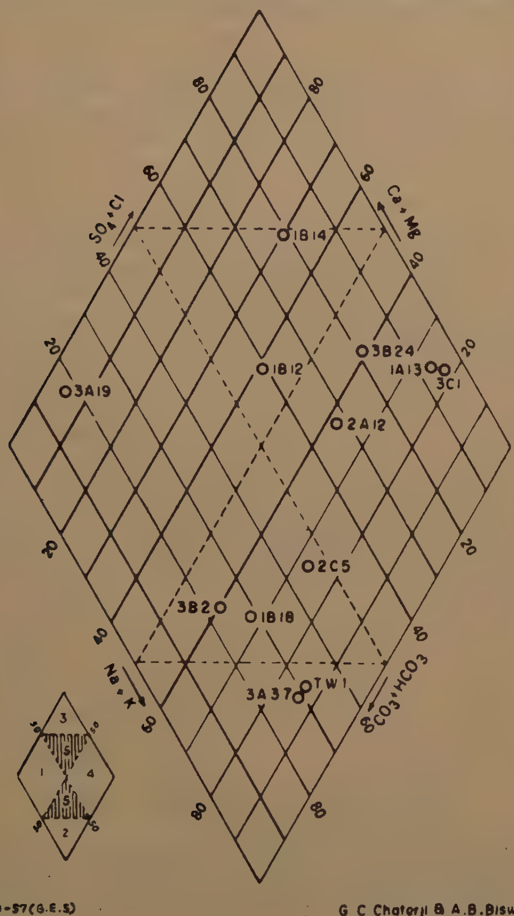


Plate V

2. A grouping in the central part of the diagram, increasing in both total solids and in contents of Na and Cl from left to right.

3. One lone analysis Well No. 53D/3-3A$_{19}$ representing a Calcium bi-carbonate water (secondary alkalinity); and

4. One lone analysis Well No. 53D/4-1B$_{14}$ representing a water containing predominantly alkaline earths among the cat-ions and with a proportionately small ratio of bi-carbonate.

Of the five analyses falling in the 1st group (sodium-bicarbonate) total dissolved solids range from 505 ppm. in sample No. 53D/4-1B$_{18}$ to 1,240 ppm. in sample No. 53D/7-3A$_{37}$. Four out of these five samples were collected from open wells tapping shallow aquifers (depth range 80-100 feet below land surface in general).

Only one sample (No. TW 1) was collected from a tube-well tapping deep aquifers. A comparison of the analysis of tube-well water with those of shallow well waters does not bring out any significant differences in character and quality with change in depth. The samples were from wells all located in the central part of the Project area, east of the central quartzite ridges. The sample of lowest total solids, collected from an open well near the bank of the Dohan *Nadi* may indicate the possibility of groundwater recharge from the Nadi during times of flow. Five samples are represented in the 2nd group. The total dissolved solids of these show a variation from 1,080 ppm. in the sample from Well No. 53D/3-1B_{12} to 8,165 ppm. in that from Well No. 53D/2-3C_1. These samples also represent chemical character of shallow groundwater.

The third group is represented by a lone analysis (No. 53D/3-3A_{19}) of a sample collected from an open dug-well located beyond the western face of the central ridges. This analysis represents a normal calcium-bicarbonate type water with a concentration of 356 ppm. of total solids. This sample is also very low in chloride content (18 ppm.). Partial analyses of several shallow dug-well samples from the area to the west of central ridges generally show similar low chloride contents. This fact shows that the chemical character and quality of shallow groundwater from beyond the western face of the central ridges is significantly different from that in the east of the central ridges.

The last group also represents a lone analysis which is characterised by a predominance of alkaline-earths among cat-ions and a low bi-carbonate-content. This sample is collected from a shallow dug well in the central part of the area.

The samples are from wells scattered almost throughout the area from extreme north to extreme south without showing any definite trend in character, thereby proving the lack of any geographical control of chemical character of groundwater in the Mahendragarh region.

The range shown by the analytical data are summarised below:

	Range (Parts per million)
Chlorides	10 - 8,000
Total hardness	40 - 8,200
Bicarbonates	120 - 2,200

The analytical data have been utilized for preparing quality of water maps showing the areal distribution and concentration of chloride and bicarbonate-ions and also total hardness (vide plates II, III, IV). Groundwater occurring in the extreme northern part and also in the east central part is highly mineralized and characterised by very high concentration of chloride-ions and total hardness. Chloride salts generally are very soluble in water and are not removed from solution by natural processes in the aquifers. Once in solution chloride remains in solution unless there is a loss of solvent and the saturation point is exceeded. The hardness of water is a measure of its content of ions of calcium, magnesium, iron, aluminium and other cat-ions that combine with an-ion of soap to form an insoluble fatty precipitate.

Maximum concentration of chloride content is found around Madhmadwi and Misri where shallow groundwater shows a concentration of chloride-ions ranging from 7 000 to 8,000 ppm. Wells situated in Rupgarh, — Jharwai — Loharheri tract yield water which is characterised by chloride content ranging between 3,000-5,000 ppm. Groundwater from Mirch, Kamod, Jhinjar, Morwala and Imlota is also highly saline (chloride content 2,000-3,000 ppm.). Other saline areas occur around Khorra, Dudhawa, Badhwana, Mondoli, Bilkara, Mahendragarh, Dongra Ahir and Korahauta.

As in about one fourth of the total area the concentration of chlorides is more than 1,000 ppm. Waters from most of the shallow wells (depth range 50-100 feet below land surface) have perceptibly to strongly salty taste. In the extreme northern parts, because of high salinity of groundwater, great difficulties are experienced by villagers for domestic supply of potable water. In these areas potable water is generally obtained from wells dug in ponds which accumulate a standing pool of water during the rainy season. This accumulation is withdrawn and evaporated out in 2 to 3 months after the rains; but sufficient local recharge of the groundwater body takes place to dilute locally the salinity of groundwater; so that the wells in the ponds continue to yield acceptable quality of water throughout the dry season. Quality of water is generally better in the areas beyond the western face of the west-central ridges where chloride contents in the groundwater are usually below 200 ppm.

The total hardness is generally very high in most parts of the area. Maximum concentration occurs in the extreme northern and east-central parts. The highest concentration of total hardness of 7,000-8,000 ppm. is found around Misri and Madhmadwi. The Rupgarh-Jharwal area shows concentration between 4,000-5,000 ppm. The tracts around Ghikara, Shamspur, Jhinjar, Mirch and Morwala are characterised by concentration varying between 2,000 and 4,000 ppm. Well-water from Dongra, Mahendragarh and Korahauta is excessively hard. High concentration of total hardness has also been noted around Bawana in the central part and around Gopalawas and Pachopakhurd in the west. Moderately soft water occurs around Balana, Dhanondah and Bhurjat. Groundwater from Sihore, Kanhara, Bhagot and Nangal is moderately to very hard.

It is found that there exists some relationship in the concentration and distribution of the chlorides and total hardness. The high spots for both the constituents occur around almost the same places therby suggesting that the hardness is due to the concentration of chlorides.

Places around Bassi and Loharheri are characterised by groundwater showing highest concentration of bi-carbonate-ions. Concentration of bi-carbonates ranges from 200 to 500 ppm. in the east-central and south-eastern parts and also in some areas in the west. In other parts the bi-carbonate concentration varies from 50 to 100 ppm. The bi-carbonate content in the groundwater of the area is in general much lower than that of the chloride content.

Analysis of the foregoing three quality distribution patterns in conjunction with conductivity results brings out certain interesting features of the groundwater of the area. Normally conductivity varies with change in the overall concentration of several common constituents rather than with change in one only. Chloride shows a more definite relationship to specific conductance than do the other two. In a generalised plot hardness seems to show two rather definite patterns. In one of these there is a trend towards a rude exponential relationship between total solids and hardness and in the other there seems to be little or no relationship at all. Of the two, the latter group is the more interesting from the stand point of geo-chemistry and suggests the possible existence of interphase ion transfer. The huge amount of scatter which is chiefly towards the bottom right probably indicates the interfingering of several patterns, plus, of course, a certain amount of analytical error.

9. Conclusion

From the study of the open-wells which exist in the Mahendragarh area it has been found that the depth to water generally ranges from 50 to 100 feet below land surface in the eastern side of the west-central ridges and also in the northern parts of the area. The shallowest depth at which recoverable water is met with is 41.5 feet

below land surface at Well No. 53D/6-3A$_7$ at Dhani. Beyond the western face of the west-central ridges groundwater often occurs at a depth of 200 feet or more below land surface. This indicates that the rocky ridges form a barrier to groundwater movement.

The capacity of open-wells tapping shallow alluvial aquifers is estimated at 500 to 3,500 gallons per hour at 10 hours of pumpage a day.

There has been a noticeable deficiency in rainfall during recent years in the southern parts of the area. It has been reported by irrigators and other water users that waterlevel in the wells dug in this area has been gradually receding in recent years. The recession is considered to be primarily due to the lack of adequate recharge. In the northern parts of the area, however, there has been no noticeable recession of the water-level in the wells.

The quality of groundwater is generally better in the western parts where chloride contents are usually below 200 ppm. Groundwater occurring in the extreme northern and east-central parts is highly mineralized and is characterized by very high concentration of chloride-ions and total hardness which may be anything between 2,000 to 8,000 ppm.

Thus the prevailing low yield of the near surface alluvial aquifers and also high salinity of groundwater do not warrant large scale development of shallow groundwater out of open-wells; although some further development may be possible in the south-western, central and extreme south eastern corners of the area where water-level is not too deep and the quality of water is fairly good. In those areas consideration may be given to deepening of wells to increase infiltration surface and storage capacity. Installation of mechanical pumps may also be considered, if cheap supply of electrical energy be available from the Bhakra-Nangal Project. With mechanical pumps it would be possible to water the land more effectively.

In the tracts of high salinity (chloride content greater than 2,000 ppm.) only plant crop of high salt tolerance may be irrigated from groundwater. Even then it would be necessary to take recourse to rotational cultivation.

10. Acknowledgement

The authors are thankful to the officials of the P. W. D., Punjab (India) for their help during the field investigation in the Mahendragarh district. The authors are also grateful to Mr. A. A. Garrett, Groundwater Engineer, U. S. G. S. for some useful suggestions during the course of the investigation and to the Director, Geological Survey of India for his kind permission to publish the paper.

BIBLIOGRAPHY

(1) Medlicott, H. B. (1874) — Note on the habitat in India of the elastic sandstone or so-called Itacolumyte — *Records of the Geological Survey of India*, Vol. VII, Pl 1, pp. 30-31.
(2) Hacket, C. A. (1881) — Geology of the Aravalli region, — Central and Eastern, *Records of the Geological Survey of India*, Vol. XIV, p. 286.
(3) Oldman, R. D. (1889) — On the Flexible Sandstone or Itacolumite with special reference to its nature and mode of occurrence in India and the cause of its flexibility — *Records of the Geological Survey of India*, Vol. XXII, Pl 1, pp. 51-55.
(4) Bose, P. N. (1906) — Notes on the Geology and Mineral Resources of the Narnaul District (Patiala State) — *Records Geological Survey of India*, Vol. XXXIII, pp. 55-61.
(5) Heron, A. M. (1917) — The Geology of north-eastern Rajputana and adjacent districts — *Memoir, Geological Survey of India*, Volume XLV, part 1.
(6) Raina, B. N. (1954) — A short note on the geology of the area around Atela and

Kaliana, Dadri — tahsil, PEPSU. (Unpublished report of the Geological Survey of India).

(7). CHATERJI, G. C., MITRA, A. and GARRETT, A. A. (1954) — Selection of site for Exploratory Bore-holes in Mahendragarh Enclave, PEPSU, under the TCM Operational Agreement No. 12 — Geological Survey of India — (unpublished report of Geological Survey of India).

(8) MITRA, A. and BISWAS, A. B. (1955) — Groundwater geology of the east central part of the Mahendragarh district, PEPSU — (unpublished report of Geological Survey of India).

(9) BISWAS, A. B. (1956) — A preliminary note on certain dune sand from the Kaliana area, Mahendragarh district, PEPSU. — (Abstract published in the proceedings of the fourty-third session of the Indian Science Congress Association, 1956).

ESSAI D'EXPLICATION DE CONSTATATIONS FAITES SUR LA VARIATION DE SALINITÉ DE CERTAINES EAUX DU SOUS-SOL BRUXELLOIS

G. TISON, jr.
Université de Gand

RÉSUMÉ

L'auteur reprend les intéressantes constatations d'Halet sur un certain nombre de puits de l'agglomération bruxelloise. D'une façon générale, Halet avait trouvé que le pompage provoquait une augmentation de la salinité. L'explication de certaines des constatations est assez analogue à ce qui a été indiqué dans la note sur la salinité des eaux artésiennes en Belgique du Nord. Un cas particulièrement intéressant est celui de l'eau d'un puits dont la salinité après avoir augmenté lors des pompages reperd cette salinité lors de l'arrêt des pompages. L'auteur donne une explication basée tant sur des considérations hydrologiques qu'hydrauliques.

1. A la suite des recherches de Delecourt (1) sur la salinité des nappes artésiennes du sous-sol de la Moyenne et Basse Belgique, il a été possible de reconnaître et de délimiter, dans ces nappes, des zones présentant des degrés de salure différents, séparées par des limites plus ou moins fixes.

Delecourt a notamment pu tracer avec une certaine approximation la limite qu'il a appelée de salure dans les eaux des diverses nappes, imposant pour cette limite le critère de la dureté totale de 6° Français.

On s'est cependant aperçu que le tracé de cette limite, en plan, pouvait subir des changements et il est question de certaines de ces modifications dans une autre note présentée à cette Assemblée (2).

Cette autre note traite notamment des variations de salinité constatées dans des puits très voisins à des temps identiques ou très rapprochés ou bien de celles qu'on a observées dans un même puits à des temps assez éloignés.

Dans la présente note nous nous proposons d'étudier un phénomène particulier assez curieux en rapport avec ceux dont il vient d'être question.

2. Les constatations qui nous serviront de base ont été faites par Halet (3). Nous reprenons ci-dessous l'exposé de celles d'entre elles qui sont particulièrement intéressantes pour leur précision et leur multiplicité. Halet présente des renseignements relatifs à six puits A, B, C, D, E, F repris à la coupe géologique schématisée à travers le sous-sol de Bruxelles, coupe empruntée au même auteur (figure 1).

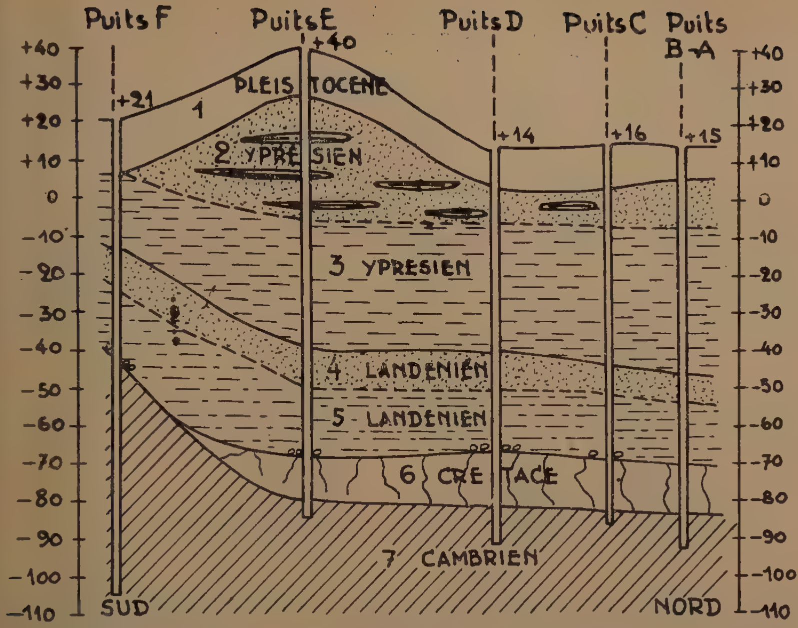
Les seules eaux qui nous intéressent sont celles des nappes captives du Landénien (Eocène inférieur) du Crétacé et du Cambrien.

3. Le puits C, foré en 1932, a atteint la profondeur de 102 m et a été arrêté à la recoupe du Cambrien. Il est tubé sur 65 m de profondeur.

Lorsque la profondeur du puits n'était que de 82 m, un essai de pompage a donné 2 m^3/h. Approfondi à 102 m ce puits a donné 4 m^3/h et après acidification 10 m^3/h et même plus.

En janvier 1933, on a noté :
Dureté totale : 28° Français

mais le régime de pompage lors de cette constatation n'a pas été noté.



COUPE GEOLOGIQUE SCHEMATISEE A TRAVERS LE SOUS-SOL DE BRUXELLES

Fig. 1

En 1935, au cours d'un pompage de 10 à 12 m³/h au moyen d'une pompe placée à 89 m de profondeur, l'analyse des eaux a donné :

Dureté totale	66° Français
Résidu sec à 100°	2,260 gr/l
Cl	0,995 gr/l
CaO	0,320 gr/l
MgO	0,072 gr/l

A remarquer l'augmentation de la dureté totale entre 1933 et 1935.

Le puits ne fut plus utilisé par suite de la dureté de l'eau, mais en 1938, dans le puits au repos, des échantillons d'eau furent prélevés à différentes profondeurs, le niveau de l'eau dans le puits étant à 37 m sous la surface du sol. Le tableau suivant donne les résultats des analyses des divers échantillons :

	Eau de 24 m gr/l	Eau de 39 m gr/l	Eau de 66 m gr/l	Eau de 86 m gr/l	Eau de 95 m gr/l
Sulfates (en ions SO_4)	0,159	0,161	0,157	0,147	0,143
Cl'	0,039	0,037	0,035	0,031	0,028
Mg	0,015	0,017	0,014	0,020	0,020
Ca	0,102	0,106	0,110	0,108	0,108
Dureté totale (français)	30°	31°	32°	32°	32°

Ainsi que le constate Halet, la composition chimique de tous ces échantillons est pratiquement la même. La dureté totale est de l'ordre de 30° pour le puits au repos, mais elle monte à 66° pour un pompage d'environ 10 m^3/h pour revenir à 30° après la cessation de ce pompage. La teneur en Chlore passe de 0,035 gr/l à 0,995 sous l'action du pompage. A remarquer encore que le tubage ne descendant pas sous 65 m, le puits peut être alimenté par les nappes landénienne, crétacée et cambrienne.

4. Le puits D a été creusé vers 1900 jusqu'à une profondeur de 94 m : il est tubé jusqu'à 84 m. D'après la coupe 1, ce puits s'arrêtait dans le Crétacé. Son débit atteignait 4 m^3/h avec une eau d'une densité de 17° Français. En 1938, le puits fut approfondi jusqu'à 105 m en pénétrant de 10 m dans le Cambrien, tandis que le tubage était descendu jusqu'à la recoupe des couches cambriennes vers 97 m de profondeur où une frette en ciment fut établie. Le débit atteignit alors jusque 27 m^3/h. Pour un débit de 15 m^3/h, l'analyse des eaux a donné

Résidu fixe à la calcination	6,490 gr/l
Cl	3,839 gr/l
SO_3	0,042 gr/l
CaO	0,506 gr/l
MgO	0,240 gr/l
CO_2 combiné	0,077 gr/l
Dureté totale (français)	100° environ
pH	8,5

Halet remarque au sujet de ce puits l'existence de deux nappes indépendantes, séparées en ce point par une couche imperméable, l'une dans le crétacé avec une dureté de 17°, l'autre dans le cambrien avec une dureté de 100°.

5. Le puit E. Ce puits terminé au début de 1936, atteint une profondeur de 125 m et pénètre dans le Cambrien. Il est tubé jusqu'à la recoupe de la craie où une frette en ciment a été établie. Le niveau de l'eau au repos s'établissait à environ 60 m sous le sol.

En juillet 1936, après un pompage de 15 jours, à raison de 8 m^3/h, l'analyse d'un échantillon d'eau donne :

Dureté totale (français)	10,2°
Résidu fixe à 100°	0,6392 gr/l
Silice	0,0231 gr/l
Oxyde de fer	0,0014 gr/l
Alumine	0,0037 gr/l
Chaux	0,0452 gr/l
Magnésie	0,0167 gr/l
Na_2O	0,2614 gr/l
SO_3	0,0142 gr/l
CO_2	0,066 gr/l
Cl	0,2664 gr/l
NaCl	0,4950 gr/l

Huit mois plus tard, en mars 1937, l'analyse donne (débit inconnu) :

Dureté totale (français)	22°
Résidu sec	1,066 gr/l
Cl	0,507 gr/l

Entre le 25 août et le 9 septembre 1937. des pompages furent exécutés avec

une pompe immergée à 120 m de profondeur. Le tableau suivant résume les constatations faites au cours de ces pompages :

	Niveau de l'eau	Débit m³/h	Dureté
25 août 1937	112 m	13,6	27°
26 »	117	13,9	30°
27 »	115	12,7	30°
28 »	111	12,8	29°
30 » (après 35 heures d'arrêt de la pompe)	75	13,2	20°
31 août 1937	106 m	11,9	30°
1 septembre 1937	114	13,2	32°

Enfin au mois de mars 1938 après un arrêt du pompage de plus d'un mois, le niveau des eaux dans le puits s'établissait vers 68 m sous la surface et des échantillons d'eau prélevés à différentes profondeurs présentaient les caractéristiques suivantes :

	Dureté	Cl
68 m de profondeur	7°8	0,190 gr/l
97 m »	7°7	0,195
117 m »	7°9	0,196

Le phénomène constaté au puits C se répète donc au puits E; disons même qu'il se précise : l'arrêt définitif du pompage réduit la dureté à 7°8 et la teneur en Chlore à 0,196 gr/l sur toute la hauteur de l'eau du puits. Un arrêt temporaire (de 35 heures) du pompage, agit dans le même sens en ramenant la dureté à 20°, alors que le pompage fait monter cette dureté à environ 30°.

6. Le puits F a une profondeur de 125 m, mais, comme le montre la figure 1, le Crétacé n'existe pas à cet endroit et le Cambrien y remonte à environ 63 m sous le niveau du sol. Entre 63 et 75 m de profondeur, le terrain cambrien est ici composé de schistes phylladeux très altérés, imperméables tandis que de 75 à 125 m, le puits recoupe des grès et quartzites. Le puits rencontre par conséquent, à cet endroit, deux nappes indépendantes, l'une, dans le gravier de base du Landénien, l'autre dans les grès et quartzites cambriens. La première possède un niveau hydrostatique s'établissant à 17 m sous le sol et elle fournit 17 m³/h pour un rabattement de 17 m. Un débit de 40 m³/h, dans cette nappe, produit des entraînements de sables landéniens. La dureté totale de cette eau est de 2° Français et elle ne contient que 0,012 gr/l de NaCl.

Quant à la nappe cambrienne, on a pu l'étudier après avoir établi une frette en ciment à la tête des roches cambriennes. Le niveau hydrostatique de cette nappe s'établit à 47 m sous le sol et les teneurs en NaCl au cours des pompages ont donné lieu aux constatations suivantes :

	Débit m³/h	Teneurs en NaCl, gr/l
22/12/38	3	0,51
27/12/38	12	0,93
30/12/38	9	0,84
31/12/38	16	0,95
4/ 1/39	20	1,02
5/ 1/39	25	1,09
6/ 1/ 39	29	1,14

7. Les puits A et B ont donné lieu à certaines constatations que Hallet n'a pu vérifier et qui ne peuvent guère conduire à des conclusions.

8. Halet avait tiré de toutes ces constatations des conclusions générales dont nous ne retenons que les suivantes :

a) Les eaux des nappes landénienne et crétacée ont des teneurs en sel peu élevées et leur dureté est relativement faible (voir notamment le puits D non approfondi).

b) Les eaux provenant des fissures du Cambrien sont dures et salines (voir notamment le puits D approfondi et tubé jusqu'à la recoupe du Cambrien).

c) La salinité des eaux du Cambrien croît avec l'importance du débit ou du rabattement.

9. Nous voudrions nous arrêter sur le phénomène dont il a été question pour les puits C et E (paragraphes 3 et 5). Ces deux puits sont alimentés à la fois par la nappe du Crétacé et par celle du Cambrien. A l'état statique, l'eau de ces puits est de faible dureté et très peu saline. Les pompages y provoquent une augmentation de la salinité et de la dureté, mais l'arrêt des pompages ramène assez rapidement aux conditions de faible dureté et salinité de l'état statique. Nous nous proposons dans ce qui suit de fournir une explication de ce phénomène.

10. Nous croyons d'ailleurs qu'il y a lieu de distinguer deux cas :

a) ou bien les deux nappes sont indépendantes et séparées par une épaisseur de Cambrien imperméable. Les constatations faites dans le cas d'une telle indépendance ont donné pour le niveau hydrostatique de la nappe cambrienne une cote inférieure à celle du niveau hydrostatique de la nappe supérieure. Lors des pompages, le puits est alimenté par les deux nappes et l'eau saline de la nappe cambrienne donne à l'eau pompée une salinité et une dureté assez prononcées, surtout si, comme c'est le cas au puits C, le Cambrien présente une plus grande perméabilité que le Crétacé. Mais lors de l'arrêt des pompages, du fait de la différence des niveaux statiques des deux nappes, le puits devient une communication entre la nappe crétacée à niveau statique élevé et la nappe cambrienne à hauteur d'équilibre moins élevée. Le puits se remplit donc d'eau crétacée, plus douce, qui refoule l'eau cambrienne dans la couche de même nom. Le puits, à l'arrêt, fournit par conséquent sur toute sa hauteur de l'eau douce. Un nouvel équilibre tend d'ailleurs à s'établir avec baisse du niveau crétacé et hausse de l'autre.

b) Ou bien les deux nappes ne sont pas indépendantes. Il semble bien que pour les puits C et E qui nous occupent, ce soit bien ce dernier cas qui soit à envisager. Ces deux puits ont en effet été arrêtés dans la partie tout à fait supérieure du Cambrien et on a cependant vu qu'ils sont fortement alimentés par la nappe de ce terrain. Ces puits paraissent donc atteindre immédiatement le Cambrien perméable sans traverser (comme le puits F) des phyllades cambriens imperméables. Dans ce cas, il n'y a, au point de vue hydraulique, qu'une seule nappe présentant un seul niveau hydrostatique, mais ayant des compositions chimiques différentes dans chacune des couches porteuses.

Le Cambrien atteint par le puits a une perméabilité assez grande (plus grande que celle du Crétacé en certains endroits comme on peut le voir pour le puits D). Lors des pompages, tout comme on l'a expliqué sous le littera *a*) ci-dessus, le puits capte l'eau des deux nappes et le mélange qui se produit dans le puits, prend de ce fait une salinité et une dureté assez nettes, plus grandes que celles du Crétacé.

Mais immédiatement après l'arrêt du pompage, le puits se trouve tout d'abord rempli d'eau assez salée sur toute sa hauteur, même à la hauteur du Crétacé, cette eau étant celle du mélange des deux nappes, d'autant plus saline que le Cambrien est plus perméable.

Par contre, dans le Crétacé se trouve partout, et notamment au bord du puits, de l'eau de faible dureté et salinité. Cette eau est par conséquent moins dense que celle qui remplit le puits et de ce fait son niveau statique à tendance à s'établir à une cote légèrement supérieure à la cote d'équilibre vers laquelle tend l'eau plus salée du puits.

Cette faible différence est cependant suffisante pour provoquer, au moins sur la partie supérieure de la paroi crétacée du puits, un écoulement de la nappe du Crétacé vers le puits. Le niveau dans le puits dépasse de ce fait la cote du niveau statique de l'eau salée et l'eau du puits exerce par conséquent sur l'eau de la nappe cambrienne une pression supérieure à celle correspondant au niveau statique de cette dernière nappe. L'eau salée du puits va par conséquent rentrer dans la nappe cambrienne par la partie inférieure du puits, provoquant une baisse du niveau du puits et par suite une nouvelle alimentation de celui-ci par l'eau douce du Crétacé, et ainsi de suite jusqu'à ce que toute l'eau du puits, jusqu'au Cambrien, soit devenue d'une densité et d'une salinité égales à celles du Crétacé.

Il s'agit en fait de deux vases communiquants contenant à l'origine deux liquides de densités différentes et présentant de ce fait une différence de niveau initiale. Mais la paroi entre les deux vases est perméable et il se produit de ce fait un passage supérieur du vase au liquide moins dense vers l'autre et une filtration de sens inverse vers le bas.

11. Nous avons pu vérifier l'explication proposée au paragraphe précédent par un essai sur modèle que nous avons effectué au Laboratoire d'Hydraulique de l'Université de Gand. Nous disposions à cet effet d'une cuve maçonnée d'un diamètre de 1 m 50 et d'une hauteur de 0,65 m. Dans cette cuve nous avons reproduit d'une façon schématisée la situation telle qu'elle se présente pour les puits C et E. Le fond de la cuve sur une hauteur de 15 cm a été rempli d'un gravier assez fin présentant

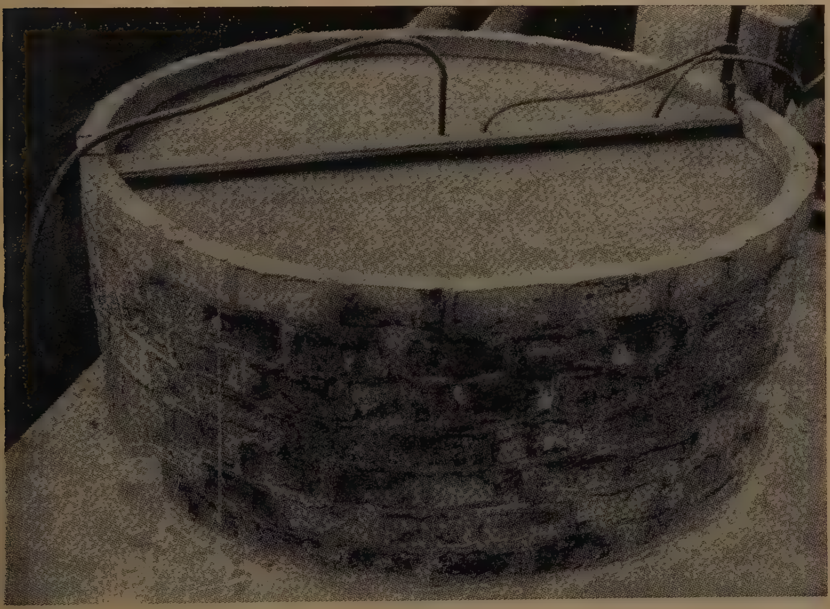


Fig. 2

2 à 5 mm de diamètre. De l'eau salée (8 gr de NaCl par litre) et colorée à la fluorescéine fut déversée dans la cuve de façon à ce que la nappe ainsi constituée vienne affleurer au dessus du gravier. On réalisa ensuite au-dessus du gravier une couche de 40 cm de sable de 0,3 mm environ de diamètre et ce sable fut saturé d'eau douce et non colorée. Le gravier représentait le Cambrien avec sa plus grande perméabilité et ses eaux salines et dures tandis que le sable reproduisait le Crétacé moins perméable mais présentant une nappe d'une salinité et d'une dureté moins prononcées.

Au centre de la cuve un tuyau perforé d'un diamètre intérieur de 14 mm était utilisé comme puits. Afin de reproduire la situation des puits C et E, ce tuyau n'atteignait qu'une profondeur de 3 cm sous le niveau de séparation sable-gravier. La partie du tuyau pourvue de perforations fut entourée extérieurement de toile de façon à éviter l'entraînement de sable. Un tuyau en caoutchouc qui s'adaptait à l'extrémité supérieure du puits permettait d'extraire de l'eau par siphonnement, le débit étant réglé par pincement de l'extrémité libre du tuyau en caoutchouc. Le modèle ainsi réalisé est reproduit sur la photo 1.

On a mesuré la salinité de l'eau extraite du modèle à différents instants pendant un essai de pompage tandis qu'après la fin du pompage on a recueilli à intervalles réguliers des échantillons d'eau dans le puits pour en déterminer également la salinité. Les observations faites sur le modèle firent apparaître le même phénomène que celui observé en réalité dans les puits C et E. C'est ainsi que pendant le pompage la salinité était supérieure à 7 gr/l, le débit étant environ 1 l/min. Cette salinité n'a guère varié pendant la durée du pompage (6 minutes). Les échantillons prélevés dans le puits après la cessation du pompage présentaient une salinité moins prononcée qui diminuait rapidement dans le temps. Huit heures après la fin de l'essai, l'eau dans le puits, sur toute la hauteur du puits était devenue complètement incolore et douce.

Ce modèle nous a donc permis de reproduire le phénomène constaté pour les puits C et E et de vérifier l'explication proposée.

BIBLIOGRAPHIE

(1) J. Delecourt — Les eaux artésiennes du Bassin de Paris, de la Basse et de la Moyenne Belgique. — *Bull. Soc. Belge de Géologie*, etc. t. XLVI, 1936.

(2) L. J. Tison — Salinité des Eaux artésiennes en Belgique du Nord. Comptes-Rendus et Rapports de l'Assoc. Intern. Hydr. Scient. — Assemblée Toronto, 1957.

(3) Halet, Quelques données nouvelles concernant la salinité de certaines nappes aquifères du sous-sol profond de l'agglomération bruxelloise, *Bulletin de la Société Belge de Géologie*, Tome XLIX, fascicule 3 (1939).

CONTAMINATION OF GROUND WATER BY OIL WELLS

Dr. FRIEDRICH NÖRING

Governmental geologist, Geological Survey of Hesse, Wiesbaden

Oil borings have begun in Western Germany in 1880. In 1956 nearly 100 oil- and gas-fields stand in production (MALZAHN 1957) with an output of 3,5 millions tons oil and 366,6 millions m^3 gas.

Western Germany has about 200 inhabitants each squarekilometer and wins the greatest part of all used water out of the ground water. Ground water is very damageable by oil and salt water contamination in connection with oil and gas exploitation. Oil- and gas-fields are situated in the environs of the large cities of Munich and Augsburg in the Southern Bavarian Plain, of Hamburg, Kiel, Braunschweig and Hannover in the Northern German Plain and of Frankfurt, Mainz, Darmstadt and Karlsruhe in the Plain of the Upper Rhine. Some oil fields coincide with the ground water catchment areas of the mentioned cities.

It exists sometimes a causal connection between the occurence of oil- and gas-deposits in greater depth and of wide-spread pleistocene aquifers with great ground water yield. The connection is given by frequent geotectonic conservativism which produced in the same area thick oil bearing permian, mesozoic and tertiary strata as well as fresh water bearing quaternary deposits in recent lowland subsidences.

Nevertheless the result of all investigations and experiences, concerning contamination of ground water in Western Germany, is calming. The usual casing depth of conductor pipe and after abandoning the well its cementation prevents from communication of oil and salt water with the fresh water formations of lower depth. Conductor pipe and cementation are ordered by mining authorities, which are instructed to protect fresh ground water from contamination.

No doubt the sulphate content of salt water which accompanies often oil and gas deposits attacks the cement. Nevertheless it seems impossible that a cement stopper of several hundred meters length can be destroyed in human times. Moreover the plastic layers of the overlaying deposits shut the borehole. Also sulphate-resistent kinds of cement are preferred.

Certainly a danger is given by blow-outs of oil, gas and salt water. In such a case a security well has to be constructed. It must reach into the upper aquifer, which only can be contamined by oil and salt water infiltration coming from earth surface or borehole to underground. The drawdown, effectuated by pumping as long as necessary, skims off the contaminated part of the ground water and protects the pure parts. The disposal of such contaminated water offers a separate problem. It is no matter of geohydrology apart from the possibility to inject the wastes into already salty deep aquifers.

Until now in Western Germany no severe contamination accident is known. Oil wells in Hesse have been drilled in less than 1000 m distance, extremely in 300 m distance, from great drinking water works.

BIBLIOGRAPHY

DROBEK, WILHELM : « Diskussions-Beiträge.» — *Gas- und Wasserfach*, **96**, p. 470, p. 474, München 1955.

GERB, LOTHAR : « Diskussions-Beitrag ». — *Gas- und Wasserfach*, **96**, p. 471-472 München 1955.

HOLLUTA, JOSEF : « Diskussions-Beitrag.» — *Gas- und Wasserfach*, **96**, p. 472, München 1955.
HOSANG, WILHELM : « Diskussions-Beitrag ». — *Gas- und Wasserfach*, **96**, p. 470-471, München 1955.
KREJCI-GRAF, KARL, FRIEDRICH HECHT & WALTER PASLER : « Über Oelfeldwässer des Wiener Beckens.» — *Geol. Jahrb.*, **74**, p. 161-209, Hannover 1957.
MALZAHN, ERICH : « Die geologischen Ergebnisse der Erdölaufschlußbohrtätigkeit des Jahres 1956 in Westdeutschland.» — *Erdol und Kohle*, *10*, p. 201-216, Hamburg 1957.
PAAVEL, VLADIMIR : « Diskussions-Beitrag.» — *Gas- und Wasserfach*, **96**, p. 473, München 1955.
RUNGE, HANS : « Erdöl, Erdgas und Grundwasser.» — *Gas- und Wasserfach*, **96**, S. 468-470, p. 473-474, München 1955.
RUNGE, HANS : « Schutz von Grundwasservorkommen in Tiefbohrungen. » — *Z. deutsch. geol. Ges.*, (1954), **106**, p. 65-69, Hannover 1956.
SCHMIDT, FRITZ : « Die Konzessionen zum Aufsuchen von Bitumen in Oberbayern und ihre möglichen Rückwirkungen auf die Trinkwassergewinnung.» — *Gas- und Wasserfach*, **95**, p. 164-168, München 1954.
—, — : « Diskussions-Beitrag.» — *Gas- und Wasserfach*, **96**, p. 471, München 1955.
WAGER, RUDOLF : « Diskussions-Beitrag.» — *Gas- und Wasserfach*, **96**, p. 473, München 1955.
WIRTH, EBERHARD : « Diskussions-Beitrag.» — *Gas- und Wasserfach*, **96**, p. 472-473, München 1955.

POLLUTION OF GROUND WATER

Prof. Dr. J. K. BAARS
Research Institute for Public Health Engineering

Drs. H. J. BOORSMA
Government Institute for Water Supply in the Netherlands

Abstract

A general consideration is given on the theoretical possibilities of mineralising polluting substances, present in surface waters by bacterial action when this water penetrates into the soil towards the ground water.

The paramount importance is pointed out of the presence of oxygen, free or in the nitrate-form. This is confirmed by results of an investigation, made of the artificial ground water schemes, now in operation in the dunes of the coastal region in the Netherlands.

An unexpected fact was that nitrate reduction turned out to be possible even when free oxygen was still present. The study of this phenomenon is continued.

At the other hand less favourable conditions were studied. In some cases mineralisation was just sufficient, in others it was not and ground water pollution, less or more serious could be detected. A description in detail is given of a case of ground water pollution by the disposal of waste from a sanatorium.

The simultaneous outbreak of three cases of tuberculosis in one family initiated a thorough examination of the individual water supplies of three country-houses and the waste-water disposal system of a neighbouring sanatorium.

It was proved that a rivulet in the direct neighbourhood of the 10 meter deep individual wells of the houses was heavily polluted by phenolic waste-water of the sanatorium.

The underground drainage failed through clogging of the drains and the underground sands layers, giving rise to a short-circuit with the rivulet by the formation of an underground canal.

In the drinkingwater of the country-houses considerable quantities of organic, phenolic and nitrogen compounds proved the contamination with the partly oxydized waste-water of the sanatorium.

Although, besides the confirmation of faecal pollution of the rivulet, no pathogenic or faecal organisms could be detected in the water of the wells, and therefore no water-borne infection of the patients seemed probable the danger of a direct infection in a further stadium of the disposal process was not fictitious. Sanitation was effected in a correction of the purification of the waste-water and the establishment of a water supply from a communal deep well.

The fate of the bacteria present in the infiltrating water was also analysed. There is a very strong adsorption to the sand particles and the bacterial count decreases strongly with depth. Although organic components are also adsorbed, these will be mostly used by the autochtonous bacteria, best adapted to the special conditions in the soil. With increasing depth and decreasing possibilities for survival the spore-forming bacteria increase in relative number. No antibiotic action could be detected in the cases under investigation.

1. Introduction

Ground water will be one of our most precious sources of drinking water in the future, as it is usually of good bacteriological quality and may, if necessary, be treated chemically without serious complications. On the other hand, surface waters are bound to become more and more polluted by man and industry.

It is therefore our duty to prevent migration of pollution towards groundwater reservoirs and to ensure that wherever polluted water penetrates into the soil, it is transformed into good ground water.

2. Theoretical considerations

Under favourable conditions the composition of polluted water penetrating into the soil may be transformed by the natural biological forces which we know to be present in the soil, and although purely physical adsorption to the soil particles may be of influence this does not involve a transformation into other components of a different character. The essential mineralization, as we know it in nature, results in end-products which are no longer subject to further transformations. When an amino acid originating from faecal matter is transformed into water, carbon dioxide and nitrates for instance, we regard this as a complete mineralization, but when it is transformed into two other components which will stimulate growth of polluting bacteria just as well, no progress has been made towards purification.

As pollution with organic matter and bacteria is still the chief problem, we shall first consider the possibility of eliminating these forms of pollution.

Since our knowledge of bacterial metabolism has increased, the theory is widely accepted that the essential reaction in this process is the transfer of hydrogen atoms from one substance to another:

$$AH_2 + B \longrightarrow A + BH_2$$

The donor loses one or more hydrogen atoms, while the acceptor becomes more hydrogenated. A great variety of organic compounds may act as donors, while the acceptors are often inorganic compounds:

Dehydrogenation	with	free oxygen	=	oxidation
»	»	nitrate	=	denitrification
»	»	sulfate	=	sulfate reduction
»	»	carbon dioxide	=	methane fermentation

Kluyver [1], who was largely responsible for this universal theory combining those of Wieland and Warburg, calls it a transhydrogenation. The hydrogen may not only be transferred to another molecule but it may migrate in the molecule itself.

$$HAB \longrightarrow ABH \longrightarrow A + BH$$

We have this reaction in the production of methane from fatty acids. Although we know from the experiments of Barker that a reduction of CO_2 in a normal methane fermentation to CH_4 is also possible, the other reaction in which a hydrogen atom from the carboxyl group shifts over to the CH_3 group is generally recognized.

In the soil the upper layers will have the greatest content of oxygen, so there we find the obligate aerobic and facultative aerobic bacteria. They are able to attack the organic substances with the aid of free or nitrate oxygen and thus perform very intense dehydrogenations. With free oxygen the end-products for final transformations are H_2O, CO_2 and nitrates.

If we come into the region of the facultative aerobic organisms, where free oxygen may be absent, the nitrates may take over the function of the hydrogen acceptor. Thus the results will be HO_2, CO_2 and mostly gaseous nitrogen.

However, it is possible that small amounts of ammonia may be formed under special conditions, as Verhoeven [2] showed.

When conditions become more anaerobic and the Redox potential decreases,

(1) A. J. Kluyver and C. B. van Niel : The microbe's contribution to biology. Harvard University Press, Cambridge, Mass., 1956.

(2) W. Verhoeven : Aerobic sporeforming nitrate reducing bacteria (Thesis) Delft, 1952.

we might enter the region where the organic components may be dehydrogenated with sulfate as an accepter (Redox potential about — 200 mV). Although the substrate becomes more and more «oxidised», the sulfate accepts so much hydrogen that H_2S is the end-product. This dehydrogenation may be very intense and even fatty acids may be broken down (3). Penetration of the organic components to a depth where these anaerobic processes are possible must be avoided.

Methane fermentation is another process which is possible in an oxygen-free medium, and although methane is a product that may very well serve as a source of energy for further bacterial transformations, it is the first member of the family of hydrocarbons, which are very stable in the subsoil. However, they are suitable for aerobic breakdown and Söhngen was the first to report on hydro-carbon-oxidising bacteria, which prevent the accumulation of fuel discharged by the heavy barge traffic in the Dutch canals. He classified these bacteria in the genus Mycobacterium.

As pollution of surface water by hydrocarbons is an increasing danger, it must be realised that nature has given us very few means to correct this kind of pollution. Under aerobic conditions it is possible, but bacteria involved in these reactions have to be present. Incidental pollution with hydrocarbons, e.g. from a plane crash in a waterworks area is seldom mineralized. The fuel penetrates into the ground-water region practically unchanged, and once the hydrocarbons have reached the ground-water they remain there unchanged. Complaints about this form of pollution of ground water are frequent nowadays.

We can list various kinds of organic substances in groups which may be broken down under certain favourable conditions, but there are some groups that cannot be transformed in any way. This for instance is the case with some of the new man-made detergents. Experience has shown that the alkyl-sulfates may be broken down in the activated sludge process and in the soil under aerobic conditions, but the alkyl-aryl-sulfonates—which have a straighter chain of carbon atoms in their structure—resist even biological action in oxidation ponds, as Neele and Hopkins (4) reported, that sulfonates from such ponds could be detected in nearby irrigation wells in concentrations of 7.5 ppm. Several towns on the Neosha River (Kansas, U. S. A.) have 6 ppm of alkyl-aryl-sulfonates in their drinking water. In the London drinking water last year the concentration of detergents was about 0.8 ppm.

This is certainly a danger for water reservoirs, as up till now we have not found a way to eliminate this pollution. The solution might be found in production of special built-up sulfonates which may be broken down by bacterial action, a possibility which is said to have been realized some months ago by the Royal Dutch Shell Laboratories at Amsterdam.

When the water contains taste components it is sometimes very difficult to eliminate these. If they were simply adsorbed to the sand particles, the distance over which they spread in the soil would increase with time. However, it has turned out that taste components in the surface water used for artificial production of ground water in the Netherlands, occasionally disappear if the detention time in the soil is long enough. Experience has shown that the «taste frontier», which may be a considerable distance away from the infiltration basin soon after starting an infiltration system, may recede in course of time. This is in accordance with the fact that bacteria may get used to breaking down certain organic components in ever-increasing quantities. Bringman (5), for instance, was able to accomplish dissimilation of quantities of as much as 1600 ppm. of phenol by cultures of Nocardia.

From the foregoing it will be clear that if mineralization takes place in the

(3) J. K. Baars : Sulfate reduction by bacteria (Thesis) Delft, 1930.
(4) J. K. Neele and G. J. Hopkins: *Sewage and Ind. Wastes*, 28 (1956), 1326.
(5) H. Bringman: *Ges. Ing.* 75 (1954), 252.

aerobic zone of the soil with the aid of oxygen, a certain concentration of polluting substances requires a corresponding amount of oxygen. If this quantity is not sufficient, conditions will become anaerobic a short distance below the surface and all unfavourable reactions may then proceed again. For example, when we infiltrate settled sewage with a BOD of 200-300 ppm, which means that 1 liter of this sewage consumes 200-300 mg of oxygen, it will be evident that it is impossible to have enough oxidising capacity in the soil for that oxygen demand.

3. Artificial production of ground water

When we analyze what happens in the artificial ground water replenishing schemes we have in Holland just now, we find that the surface water in the infiltration system of the town of Leyden—which uses aeolian sand deposits (dunes) near the coast—originally has a $KMnO_4$ number of 60 ppm. This value decreases during infiltration to 20, which means that a quantity of 10 mg O_2 is used. The local situation is illustrated in Fig. 1.

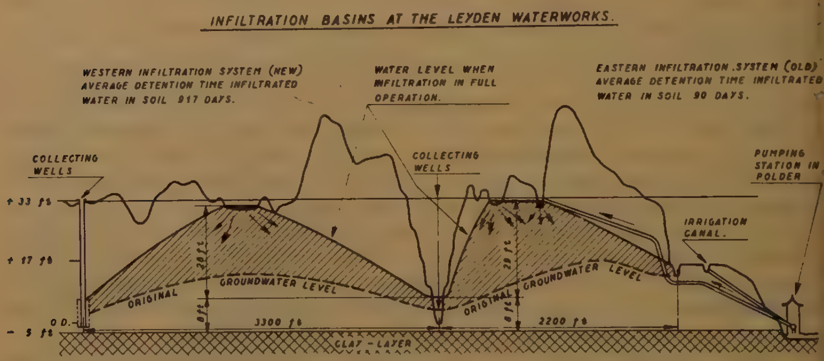


Fig. 1

Conditions for aerobic purification are quite good. The water itself may contain about 10 ppm O_2, but in sunlight the algae often cause supersaturation up to 100%. Another 5 mg/l may be obtained from the nitrates, which makes 25 mg. The system applied is intermittent, as during summer the infiltration is stopped and the water level sinks. The subsoil is then filled with air and a calculation reveals that considerable quantities of oxygen penetrate into the soil. If we assume for these infiltrations the same efficiency of 50% as Imhoff does for subsoil filters, this means that there is plenty of oxygen available for mineralization of the organic components dissolved in the water.

The decrease of dissolved oxygen and nitrate oxygen is given in Table 1, from which it will be seen that the nitrates take part in the process of mineralization even when the free oxygen is not yet fully consumed.

TABLE 1

Chemical analyses of infiltrated water at different distances from pond in p.p.m. Depth about 10 ft below surface level

ppm	O_2	NO_2	NO_3	NH_3	Org. matter as ppm $KMnO_4$
pond	14.2	10.9	0.04	1.1	58
18 ft dist.	7.5	10.5	abs.	trace	41
100 ft »	4.1	7.3	0.10	trace	31

In samples taken at the same distance from the infiltration pond but at a depth of 50 ft, so that the path of infiltration is much longer, all free oxygen as well as all nitrate oxygen is consumed.

4. Pollution of the subsoil

When pollution is much more intense, analyses show the following results. At a camping site near Hilversum about 400 cabins are erected every spring, being there from April till the end of August. About 10,000 kg of faecal substance and 400 m^3 of urine are deposited in the pit-privies, which are about 3-4 ft deep. Systematic sampling around these pit-privies during the winter season showed that mineralization in this dry aerated soil was very intense (see Table 2).

TABLE 2

Total nitrogen content in mg. of 20 samples of 1 gr soil in the upper 6 ft of soil

	NH_3–N	NO_3–N+NO_2–N	Total N
Sept. 1951	2.4434	0.6614	3.1048 (100%)
Jan. 1952	1.3927	0.5491	1.9418 (68%)
March 1952	0.5392	0.2108	0.7500 (24%)

The ground water table was about 10 ft below the ground surface, so there is a possibility that some pollution reached this area. However, no traces of pollution could be detected in the well water which was collected from 120 ft below level.

If conditions are less favourable pollution of the subsoil may migrate towards the ground water — with serious consequences as explained below.

5. Pollution of the ground water

The sudden and simultaneous occurrence of three cases of tuberculosis in one family living in the neighbourhood of a sanatorium led to a thorough examination

of the individual water supplies of two bungalows and a cottage in a rural district in the central part of the Netherlands. At the start of the investigation each of the houses was equipped with an individual supply from a drilled well 10 meters deep. The sub-surface of the region mainly consists of coarse sands and gravels, dating from Middle Pleistocene times.

During the penultimate glacial period (the Saale period) some of these deposits were thrust up by the ice front into the «push moraines» of the Eastern Veluwe. Loam lenses have been found locally, possibly dating from the Neede period, the warm interglacial period preceeding the Saale glacial period.

FIG. 2

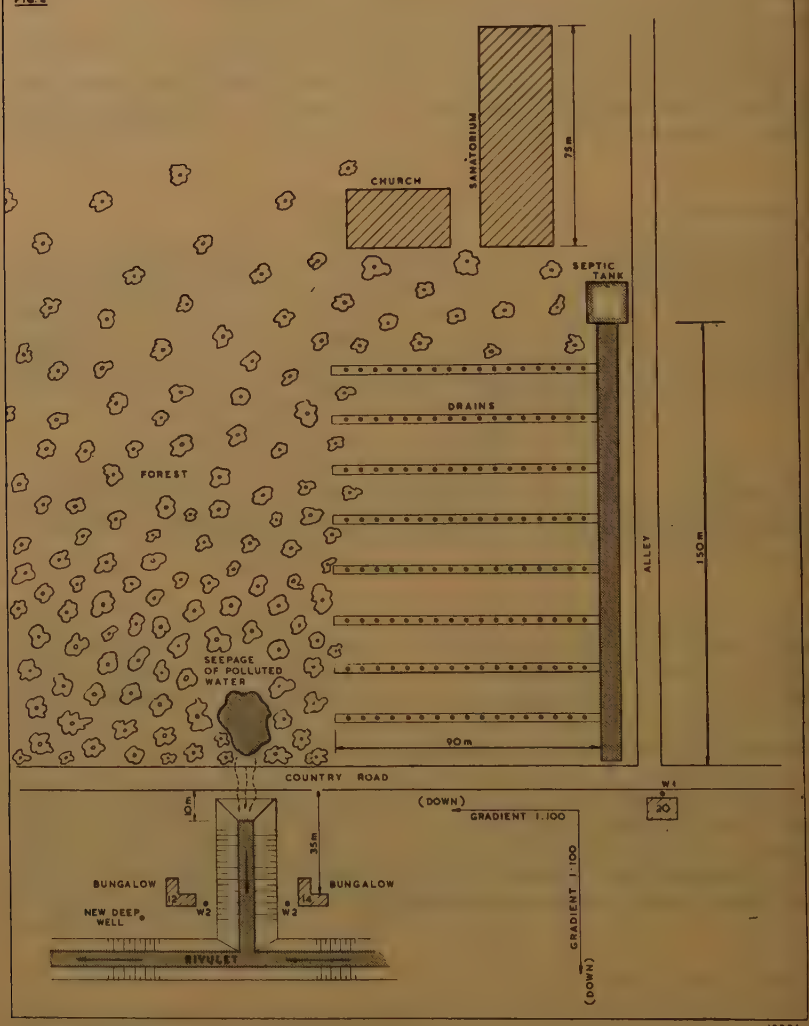


Fig. 2 — Schematic plan of the surroundings of the Sanatorium.

The greater part of the region is covered by a thin layer of so-called cover-sand, an aeolian sand deposited during the last glacial period, the Weichsel period.

In general it may be said that impermeable layers are absent. Fig. 2 gives a schematic view of the situation. The waste water from the sanatorium was only sterilized by abundant use of phenolic disinfectants and then allowed to settle in a septic tank, the overflow water being disposed of in a small open canal serving as a feeder for an underground drainage system in cultivated fields.

An inspection of the waste-disposal system of the sanatorium revealed that in course of time a surface seepage of black phenolic waste had been created in a pine forest outside the fields.

The gradients of the fields are indicated in Fig. 2; they are about 1 : 100.

It seems reasonable to expect an initial start of the clogging of the drainage system nearest to the sanatorium and the inlet in the feeder canal.

The clogging process in the drains and the subsoil caused an underground short-circuit with the spring of a rivulet between the bungalows (12 and 14) through the formation of an underground channel, finally ending in the sandy banks of the rivulet.

This caused a direct contamination of the rivulet with the barely filtered waste water of the sanatorium.

The water of the three individual wells (W 1, W 2 and W 3) and of the rivulet was examined.

The chemical and bacteriological results are summarized in Table 3. Although the search for pathogenic organisms yielded no results, chemical analysis of the well water of W 3 showed a strong biochemical transformation of organic substances into ammonia and nitrates, whereas all the samples contained a varying amount of phenolic substances.

The water of the wells W 1 and W 2 near the bungalow (14) where the outbreak of tuberculosis occurred, was still found to be almost pure from a chemical point of view, except for the phenolic components already mentioned.

Owing to the inhibitory effect of the phenolic substances, the bacteriological examinations showed a complete absence of normal pure-water bacteria. In the water of the rivulet near the spring, and even more at a distance of some hundred meters from the spring, a faecal contamination could easily be detected by the presence of E. coli, in spite of the phenolic substances.

The investigation showed that the biochemical purifying capacity of the undisturbed sandy layers was apparently still satisfactory, as the presence of unconverted phenols makes every bacteriological examination somewhat doubtful. The viability of the pathogenic germs, enfeebled by toxic substances, is an unknown and unsafe factor.

Sanitation of the water supplies of the houses was effected by elimination of the underground infiltration of the waste water from the sanatorium in the neighbouring field, together with an improvement in the purification of the waste water and the establishment of a water supply for the houses from a deep communal well.

At a depth of 50 meters the ground water proved to be completely free from any trace of contamination from a chemical and bacteriological viewpoint.

We may conclude that for mineralization of a chemical pollution certain conditions have to be fulfilled in the soil. If the substances are not suitable for transformations, as is the case with sodium chloride for instance, there is no possibility of eliminating these components from the water and infiltration of such waters is simply impracticable.

If purely chemical reactions in the soil give rise to difficulties, it is sometimes possible to treat the water before infiltration as described in the following example.

TABLE 3

Quality of surface water and ground water in the neighbourhood of sanatorium

Chemical Examinations mg/l	Spring of rivulet	Rivulet 200 meters from spring	Well W 1 depth 10 meters	Well W 2 depth 10 meters	Well W 3 depth 10 meters
Permanganate number (ppm $KMnO_4$)	17	3	5	3.5	1.3
Chloride	30	15	70	10	11
Nitrite		trace	1.1	0	0
Nitrate		trace	110	trace	trace
Sulphate		11	12	11	5
Bicarbonate		36	21	37	36
Carbon dioxide			20	7	7
Ammonia		1.0	7.0	0.1	trace
Total hardness (ppm $CaCO_3$)	26	30	89	32	26
Phenols mg/l	300	50	50	100	35

Bacteriological Examination	Number of samples		Number of samples		Number of samples					
	neg.	pos.	neg.	pos.	neg.	pos.	neg.	pos.	neg.	pos.
Eykman fermentation test 25 ml	2	0	1	1	2	0	2	0	2	0
10 ml	1	1	0	2	2	0	2	0	2	0
1 ml	2	0	2	0	2	0	2	0	2	0
Completed coli test 50 ml	1	1	0	2	5	0	5	0	5	0
10 ml	5	0	3	2	2	0	2	0	2	0
Colony counts at 37° C	0		5		0		0		0	
2 × 24 h incubation at 22° C	0		3		0		0		0	

In the eastern part of the Netherlands nowadays there is a lot of oil-well drilling. The oil produced is a heavy one, accompanied by water with about 12,000 ppm of NaCl. It is quite impossible to get rid of this water in canals or ditches, so the only

alternative is to put it back into the soil. This water is oxygen-free and contains the usual ferrous salts. The oil is separated from the water by flotation, and so some of the ferrous components are transformed into ferric components which remain suspended in the water. To eliminate all iron, the water is aerated so that the ferric floc can be filtered off, but the water is still unfit for infiltration in an anaerobic medium at —3000 ft since the oxygen would cause clogging around the infiltration pipes by ferric components in situ.

Therefore the oxygen must be removed as well. This is accomplished by spraying the water in a vacuum and absorbing the last traces of oxygen with sulfur dioxide. Chemical pollution of the ground water can thus be eliminated.

6. The fate of the bacteriological pollution

However, we should not restrict our observations to the chemical components but focus our attention also on bacteria which might be present in the water.

When polluted water is used for infiltration into the soil, we may have a great help in the self-purification which takes place in the usual infiltration ponds. The number of bacteria may decrease considerably.

Then the water penetrates into the soil and seeps slowly down through the capillary zone (if there are no fissures or cracks), the velocity of flow depending on the difference in level between the infiltration ponds and the drainage wells, or the slope of the ground water level. Our investigations have shown that a very strong adsorption takes place on the surface of the sand grains.

When infiltrating water of 1000 bact/ml, the wet sand in the upper layers may contain 500,000 bact/gram. This number diminishes with increasing depth. In Fig. 3 the bacterial counts are plotted against the depth. When the infiltration distance is long enough the sand will ultimately contain the same very low number of bacteria as is present in virgin dune soil.

Analyses show that besides bacteria organic matter is strongly absorbed in the upper layers, but one might ask whether these organic components will be dissimilated by the autochtonous bacterial flora or by those which—although present in the water—are quite alien in such a medium.

When we consider what happens in storage reservoirs, where the decrease of E. coli is greater than the decrease of the total bacterial count, we must conclude that most of the organic food in the soil will also be used by the soil bacteria which were already present, so that the penetrating microorganisms mostly starve.

Only those that are accustomed to a poor supply of nutrient will be able to survive in deeper layers. When we investigate the concentration of spore-forming bacteria we find a rise in the percentage of the total number of bacteria from 10% sometimes up to 40%.

E. coli could rarely be detected in the soil under consideration at a greater depth than 10 ft. It may be pointed out that this was wet soil, whose capillaries were almost completely filled with water, but a sufficient amount of oxidising components was present to mineralize nutritive substances.

If conditions should become anaerobic, a contamination reaching the ground water zone may remain there as such for a very long time.

Another question which arises is whether there is any indication of antibiotic action in the upper layers of the soil which might add to the purifying capacity of the soil.

We were not able to find any evidence of this. When we consider where and when antibiotics are formed, however, it is not surprising, as this only takes place after abundant growth in a normal medium (or normal growth in a special medium, rich

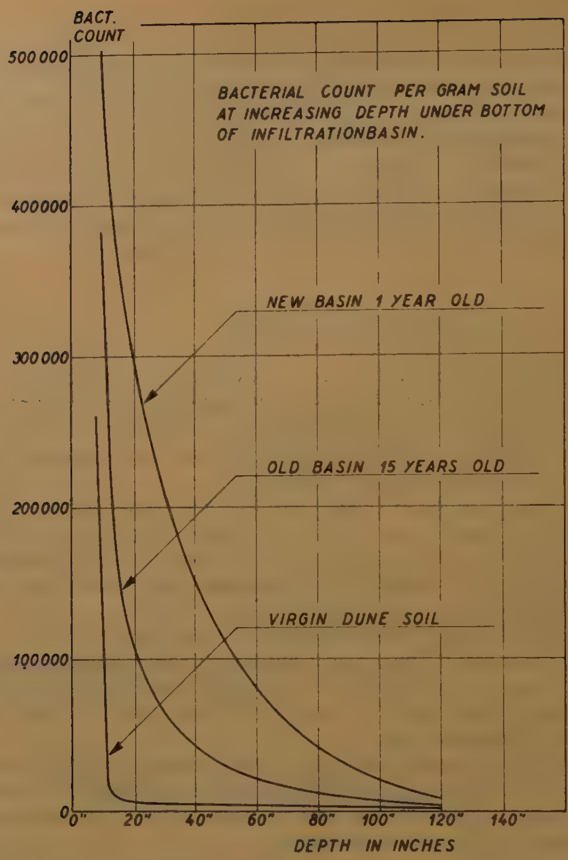


Fig. 3

in growth-promoting components). None of these conditions is fulfilled in the upper layers of the soil.

Summary

A general consideration is given on the theoretical possibilities of mineralising polluting substances, present in surface waters by bacterial action when this water penetrates into the soil towards the ground water.

The paramount importance is pointed out of the presence of oxygen, free or in the nitrate-form. This is confirmed by results of an investigation, made of the artificial ground water schemes, now in operation in the dunes of the coastal region in the Netherlands.

An unexpected fact was that nitrate reduction turned out to be possible even when free oxygen was still present. The study of this phenomenon is continued.

At the other hand less favourable conditions were studied. In some cases

mineralisation was just sufficient, in others it was not and ground water pollution, less or more serious could be detected.

A description in detail is given of a case of ground water pollution by the disposal of waste from a sanatorium.

The simultaneous outbreak of three cases of tuberculosis in one family initiated a thorough examination of the individual water supplies of three country-houses and the waste-water disposal system of a neighbouring sanatorium.

It was proved that a rivulet in the direct neighbourhood of the 10 meter deep individual wells of the houses was heavily polluted by phenolic waste-water of the sanatorium.

The underground drainage failed through clogging of the drains and the underground sand layers and a short-circuit originated with the rivulet by formation of an underground canal.

In the drinkingwater of the country-houses considerable quantities of organic, phenolic and nitrogen compounds proved the contamination with the partly oxydized waste-water of the sanatorium.

Although, besides the confirmation of faecal pollution of the rivulet, no pathogenic or faecal organisms could be detected in the water of the wells, and therefore no water-borne infection of the patients seemed probable, the danger of a direct infection in a further stadium of the disposal process was not fictitious. Sanitation was effected in a correction of the purification of the waste-water and the establishment of a water supply from a communal deep well.

The fate of the bacteria present in water which is infiltrating into the soil was also analysed. There is a very strong adsorption to the sand particles and the bacterial number decreases strongly with depth. Although organic components are also adsorbed, these will be mostly used by the autochtonous bacteria, best adapted to the special conditions in the soil. With increasing depth and decreasing possibilities for survival the spore-forming bacteria increase in relative number. No antibiotic action could be detected in the cases under investigation.

The first author is indebted to the World Health Organization for permission to use material from his publication «Travel of pollution and purification en route in sandy soils» prepared for the Fifth European Seminar at Helsinki 23-28 July 1956 in this paper.

SALINITÉ DES EAUX ARTÉSIENNES EN BELGIQUE DU NORD

L. J. TISON
Professeur à l'Université de Gand

1. Si on fait une coupe Sud-Nord des terrains constituant le sous-sol de la moitié Nord de la Belgique, on constate que toutes les couches, du primaire aux dernières strates du tertiaire, sont inclinées vers le Nord avec des pentes qui ne varient que dans de faibles limites, en général de 3 à 6 m par Km.

Une telle disposition de terrains comprenant une superposition de couches, les unes perméables, les autres imperméables, devait évidemment conduire à la naissance d'une série de nappes artésiennes, alimentées dans leurs zones d'affleurement qui se succèdent également du Sud vers le Nord.

Six niveaux aquifères au moins ont pu être repérés, ces niveaux ne se rencontrant pas nécessairement sur une même verticale : ils ne pourraient se trouver que tout au Nord du pays où les formations néogènes viennent se superposer aux autres couches tertiaires. Même là, cependant, les lacunes stratigraphiques réduisent le nombre indiqué.

Ajoutons d'ailleurs que, très souvent, certains des niveaux mentionnés se subdivisent à leur tour par suite du partage de la nappe initiale par des formations imperméables non continues. Le tableau ci-dessous donne une idée des couches porteuses de ces nappes artésiennes avec la mention de la formation qui assure leur séparation des couches perméables supérieures et réalise de ce fait leur caractère « artésien ».

Couche porteuse	Couche imperméable supérieure
1. Néogène	Argile de Tegelen
2. Oligocène	Argile de Boom
3. Eocène (Lédo-Panisélien)	Argile d'Assche
4. Eocène (Yprésien)	Argile de base du Panisélien
5. Eocène (Landenien)	Argile Yprésienne
6. Crétacé et Primaire (parfois aussi sables « heersiens » de la base du Tertiaire).	Argile Landenienne.

Il y a souvent plusieurs formations artésiennes plus ou moins distinctes dans le Néogène et dans le Landenien. Dans le Crétacé et le Primaire, où se trouve le « Grand Courant » des puisatiers, celui-ci se subdivise souvent en deux branches importantes. séparées par des formations imperméables du Hervien ou des schistes houillers. La branche supérieure se loge dans les formations du dessus du Crétacé, tandis que la branche inférieure est particulièrement portée par le calcaire carbonifère et en son absence par des terrains plus anciens.

La figure 1 donne la situation dans le Limbourg aux environs de Beringen où le nombre de couches artésiennes est réduit à 2 ou 3, car à certains endroits plusieurs niveaux aquifères peuvent se loger dans les couches landeniennes.

2. L'étude de la salinité des nappes du Nord de la Belgique fut entreprise par J. Delecourt 1) dont les exposés sont devenus classiques.

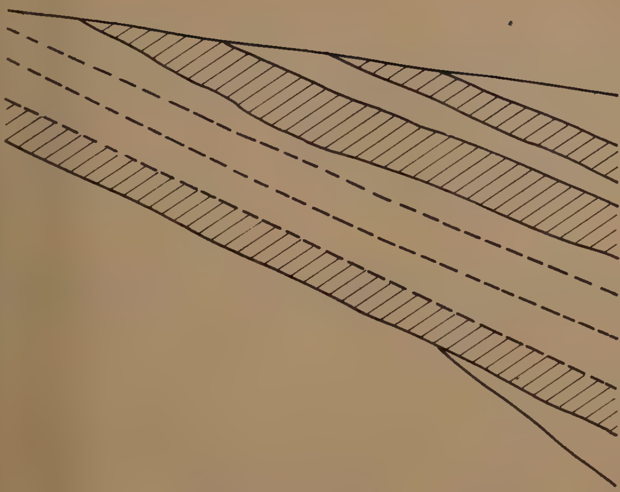


Fig. 1

Dans son étude de 1936, il écrit :

« Chaque courant artésien, pris isolément, comprenait plusieurs zones dont les eaux présentaient des caractères chimiques très différents.

En Belgique, les eaux de la première zone, voisine de la nappe phréatique, sont franchement dures. La dureté est d'abord due à la présence de carbonate de chaux dans les limons pléistocènes. Elle est due aussi à l'abondance des formations calcaires du Crétacé et du Dinantien... ». Or, constate Delecourt, bien que les courants artésiens soient alimentés au Sud par des eaux phréatiques dures, on remarque qu'à une certaine distance de leur zone d'alimentation, ils deviennent chargés de sels alcalins et surtout de bicarbonate, de sulfate et de chlorure de Sodium et il conclut que, dans une certaine zone intermédiaire, il y a un échange de bases et addition de chlorure de sodium. Il s'est attaché à trouver ce qu'il a appelé la « limite de salure » séparant la première zone considérée (qu'il appelle zone dessalée avec une dureté supérieure à 6° Français) d'une deuxième zone dite à eaux salées avec une dureté inférieure à 6°. Le résidu à 100° pour la première zone est inférieur à 0,5 gr/l; il est compris entre 0,5 et 3 gr/l pour la seconde.

Delecourt constate que, plus au Nord encore, donc en s'éloignant de la zone d'alimentation, les eaux redeviennent dures et beaucoup plus chargées : c'est la troisième zone qu'il appelle de « sursalure » où la dureté est due à la présence de sulfates de chaux et de magnésie ainsi que de chlorure de magnésie.

3. Nous avons trouvé des idées tout aussi intéressantes dans les remarquables études du Professeur Schoeller (2).

La composition chimique de l'eau d'une même nappe, dit-il, peut changer d'amont en aval. Il se produit à peu près toujours une concentration par dissolution, les rapports :

$$r\,Cl/r\,SO_4,\ r\,Mg/r\,Ca,\ r\,Na/r\,Ca,\ r\,Na/r\,Mg$$

ont tendance à augmenter. Et insistons particulièrement sur la remarque suivante

de M. Schoeller : « Naturellement plus le trajet est long et plus la vitesse des filets liquides est petite, plus ces diverses variations s'accentuent vers l'aval ».

Notons encore l'observation suivante : « Les terrains ne sont pas toujours homogènes dans l'étendue d'une nappe et des filets liquides assez voisins circulant dans des matériaux différents peuvent différemment dissoudre les substances et par là varier leur composition chimique.» Le même auteur, revenant sur l'influence de la vitesse de circulation, observe que dans des nappes, ou des parties de nappes, sans circulation, la concentration peut se faire totalement, ce qui conduit à des teneurs considérables en sels dissous, teneurs que le « lessivage » par une nappe en mouvement diminue certainement.

4. La figure 2 donne le tracé des limites de salure et de sursalure pour diverses nappes, d'après Delecourt. L'examen de la limite de salure du Grand Courant (qui

Fig. 2

va nous intéresser particulièrement) présente certaines caractéristiques et notamment deux refoulements très marqués de cette limite vers le Nord, entre Bruxelles et Louvain d'abord et surtout dans le Limbourg ensuite, pour la branche supérieure, c'est-à-dire celle du Crétacé et même du dessus du Crétacé.

Nous avons rapproché cette configuration de la carte donnant l'étendue et les épaisseurs du Crétacé en Belgique (figure 3), d'après Legrand.

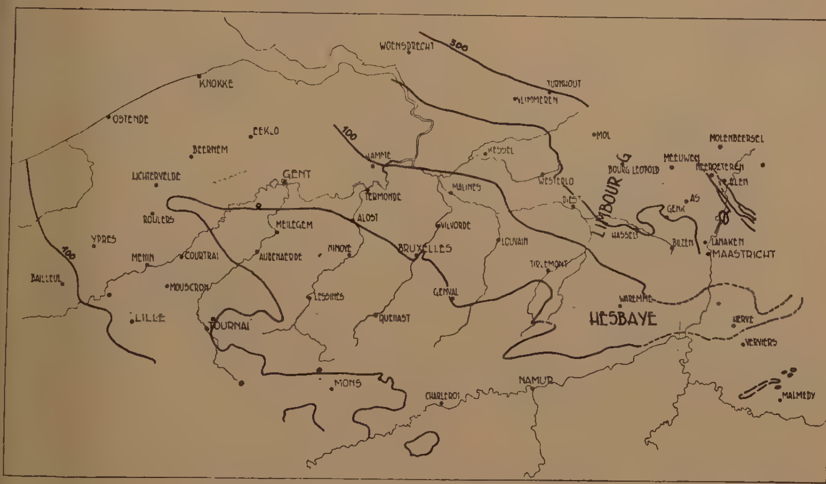


Fig. 3

La ligne O marque l'origine de ces couches et on voit que toute la partie centrale du pays est dépourvue de Crétacé. On constate aussi que les deux refoulements vers le Nord de la limite de salure du Grand Courant, branche supérieure, correspondent précisément à deux extensions ver le Sud du massif Crétacique du Nord du pays. Cette extension est particulièrement marquée au Sud du Limbourg où le Crétacé affleure (sous une faible épaisseur de Quaternaire) sur toute la Hesbaye. Cette vaste étendue de réception, à une cote relativement élevée pour la région qui nous occuper jointe à la grande perméabilité du Maestrichtien (sommet du Crétacé) et d'une partie du Heersien (Eocène inférieur) doit donner des valeurs assez élevées au débit du Grand Courant supérieur dans cette région. Il a dû en résulter (voir les considérations de Schoeller) un « lessivage » important des couches considérées, avec comme conséquence, une extension marquée de la zone dessalée vers le Nord, dans le sens du mouvement.

5. *a*) Pour chacune des nappes qui nous occupent, les considérations des deux auteurs cités conduisent à l'accroissement bien connu de la salinité en se déplaçant du Sud vers le Nord, ainsi qu'à la diminution de la dureté, cette dernière considération n'étant cependant valable qu'aussi longtemps qu'on ne s'avance pas trop vers la région de sursalure.

La figure 4 montre cette décroissance de la dureté pour la branche supérieure du Grand Courant dans la région Ouest du Limbourg. Aux environs de Beringen, et notamment à Heusden, les eaux du Maastrichtien sont encore de la première zone, mais cette figure 4 montre que la dureté de 50° F des eaux de cette nappe, au sud

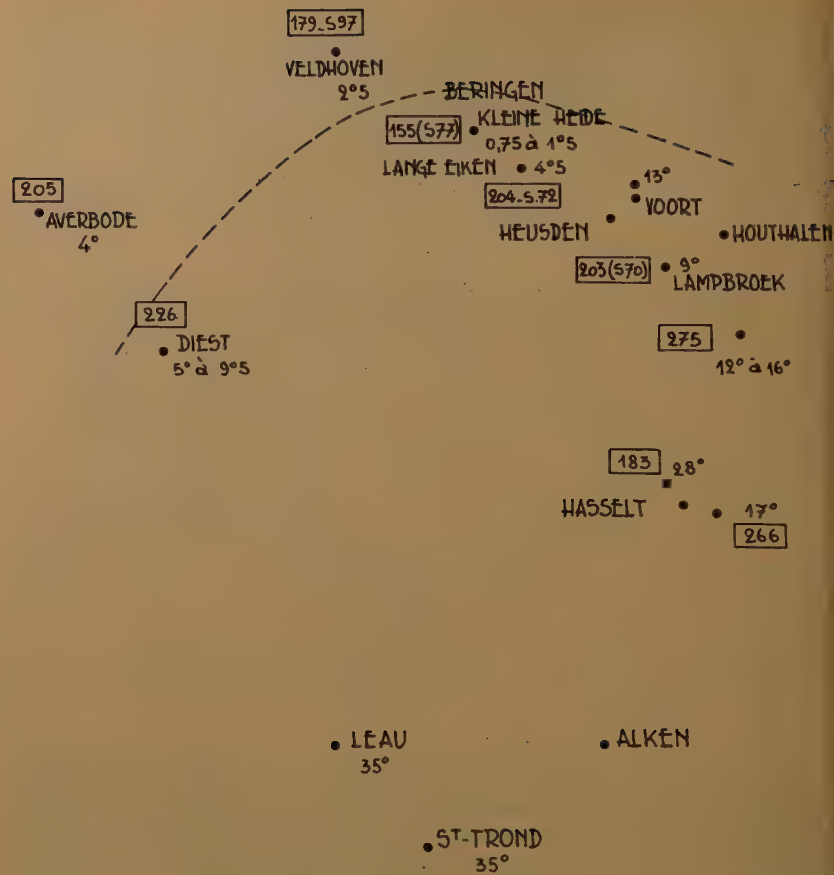


Fig. 4

du Limbourg, n'est plus que de 35° F à Léau, pour tomber à 13° F au puits de Heusden en 1949. La dureté diminue donc bien vers le Nord et, à Heusden, on se rapproche de la zone de salure, d'après les chiffres ci-dessus. Remarquons que ce puits n° 1 de Heusden a 400 m de profondeur et ne pénètre que de 23 m dans le Maastrichtien

b) Cette même figure 4 montre cependant des anomalies au voisinage de Heusden. Ainsi, légèrement à l'Ouest de cette localité, dans un sondage de Beringen (Kleine Heide), la dureté n'est guère que de 1° F et plus au Sud, à Lambroek (puits 203, Sondage 70) et à Weyvenheide (non représenté sur la carte, mais dans le voisinage du précédent) elle n'atteint respectivement que 9° F et 8° F.

En se basant sur la décroissance de dureté vers le Nord, on s'attendrait à trouver tant à Kleine Heide qu'à Lambroek et à Weyvenheide, une dureté plus grande qu'à Heusden. Remarquons au sujet de ces trois derniers puits qu'ils traversent le Maastrichtien et pénètrent profondément dans le Sérnonien.

Ajoutons encore qu'un deuxième puits creusé à Heusden, à proximité du premier, mais profond de 440 m et pénétrant d'environ 13 m dans le Sénonien après avoir traversé le Maastrichtien, a donné en 1956 une dureté de 5°6 F.

c) Dans le même ordre de constatations, remarquons qu'autour de Hasselt, on trouve de multiples puits atteignant le Maastrichtien et le Heersien et donnant des duretés variant de 17° à 36° F dans une zone d'étendue limitée (les indications relatives à ces puits ne se trouvent pas sur la figure 4).

d) On constate d'autre part des variations de la dureté dans le temps. Ainsi le premier puits de Heusden que nous avons signalé (paragraphe *a*) avec une dureté de 13° F avait effectivement cette dureté en 1949, mais en 1956, elle était devenue égale à celle du deuxième puits de la même localité, c'est-à-dire 5°6 F.

6. *a*) L'examen de ces diverses constatations nous fait penser que l'identification, au point de vue chimique, de l'eau d'une nappe ne peut être faite uniquement par la désignation de la nappe et par les coordonnées géographiques du puits.

D'autres influences, qui sont loin d'être négligeables, sont à prendre en considération et nous voudrions nous étendre quelque peu sur l'action de la profondeur atteinte par le puits dans la nappe considérée et aussi sur l'action des pompages dans ce puits.

b) Ces influences seraient nulles s'il s'agissait d'une nappe isolée, parfaitement homogène, mais telle n'est pas la branche supérieure du Grand Courant. Nous avons vu en effet que cette nappe est établie dans les terrains perméables de la base de l'Eocène (Heersien), quand ils existent, dans le Maastrichtien et dans le Sénonien. Dans la région qui nous occupe (Beringen-Zolder et plus au Sud), le Heersien ne paraît guère perméable et la nappe est portée par le Maastrichtien, relativement très perméable (d'environ 50 m d'épaisseur) et par le Sénonien (sur environ 135 m) qui semble assez peu perméable, sauf dans sa partie supérieure. Le tout repose sur des marnes herviennes imperméables.

c) Chacune de ces couches donne lieu à un écoulement de la zone d'infiltration au Sud (à des cotes voisines de 100 m) vers les régions du Nord-Nord-Est. Cet écoulement se produit naturellement, en l'absence de tout pompage.

Mais la superposition des couches perméables (mais dont la perméabilité est différente) dont nous avons parlé au paragraphe 6 *b* pose des problèmes dont la solution peut être facilité par certaines des considérations émises aux paragraphes précédents et notamment par certains des résultats de Schoeller. Bien que les eaux du Maastrichtien puissent passer dans le Sénonien et réciproquement, la vitesse d'écoulement beaucoup plus faible dans cette dernière couche y réalise une plus grande salinité, une plus forte teneur en chlorures que dans le Maastrichtien où la plus grande perméabilité produit des vitesses plus élevées.

Un puits n'atteignant que le Maastrichtien ne donnera par conséquent (au moins au débit du pompage) que des eaux de cet étage, c'est-à-dire des eaux restées dures par suite du lessivage profond auquel il a été soumis par un écoulement abondant. Ces eaux seront encore celles de la première zone dont il a été question au paragraphe 2.

Les conditions sont évidemment toutes différentes quand le puits traverse le Maastrichtien et pénètre dans le Sénonien dont les eaux plus salines se mélangent alors à celles du Maastrichtien. On voit donc que l'eau d'une nappe (le Grand Courant, branche supérieure par exemple) peut avoir une composition qui n'est pas déterminée par les coordonnées géographiques du puits et que la connaissance de la profondeur du puits, dans cette même nappe, peut exercer une influence.

7. *a*) Mais il est facile de voir que les conditions du début du pompage, exposées au paragraphe précédent, ne se maintiendront pas, ce qui fait que l'explication donnée n'est pas complète. Nous estimons que la théorie des écoulements de filtration peut ici nous donner des indications du plus grand intérêt.

En fait, la dépression (dans le sens de diminution de pression pour notre nappe

artésienne) provoquée par la mise en action du puits considéré, se propage dans la couche aquifère en y provoquant une détente et par conséquent une « libération » de l'eau décomprimée. Il s'établit donc un mouvement non permanent dont la zone d'action s'étend sans cesse. Ce mouvement tend vers une situation d'équilibre qu'on peut imaginer comme étant celle correspondant au moment où la mise en mouvement de l'eau atteint les limites de la nappe et y reçoit, à une cote constante, un débit constant égal à celui qu'elle cède au puits, sous un rabattement constant.

On peut aborder l'étude du mouvement non permanent ci-dessus grâce aux efforts de Theiss, Wenzel, Jacob et d'autres. Mais dans le cas qui nous occupe, différentes circonstances rendent le problème inextricable : les puits n'atteignent pas la couche imperméable (puits incomplets), la couche perméable n'est pas homogène mais est constituée d'au moins deux strates de perméabilités différentes, etc.

b) Dans ces conditions, force nous est de nous rendre compte de ce qui se passe avec la seule aide de la théorie dite de l'équilibre, c'est-à-dire en admettant un tracé des lignes de courant correspondant au mouvement permanent limite. L'explication ainsi obtenue ne sera sans doute qu'approximative, mais elle nous paraît suffisante pour permettre de se rendre compte des discordances et variations des salinités constatées.

Le mouvement permanent vers les puits envisagés est un mouvement à potentiel de vitesses dont on ne peut guère aborder l'étude que par une méthode graphique analogue à celle qu'on appelle parfois de Präsil. Les lignes équipotentielles hauteurs piézométriques constantes, $h = \text{Cte}$ et les lignes de courant, $\psi = \text{Cte}$ sont tracées par éléments perpendiculaires entre eux. Dans le cas qui nous occupe, l'écoulement est radial et on n'a par conséquent pas l'égalité de longueur de ces éléments ($\Delta s_h = \Delta s_\psi$ pour $\Delta h = \Delta\psi$) comme dans la méthode de Präsil, mais par contre $\Delta s_h = r\,\Delta s_\psi$, r étant la valeur de la distance du point considéré à l'axe du puits.

D'autre part, pour tenir compte de l'existence de deux couches superposées, la supérieure de permabilité K_1 plus grande que celle de l'autre K_2, le nombre de lignes de courant dans la couche plus perméable sera réduit dans le rapport $\frac{K_2}{K_1}$, tandis qu'à la surface de séparation :

$$\frac{\operatorname{tg}\alpha_2}{\operatorname{tg}\alpha_1} = \frac{K_1}{K_1}$$

(voir Tison, Cours d'Hydraulique — tome II).

c) Ces considérations rapidement rappelées, envisageons des puits s'enfonçant différemment dans la nappe considérée ci-dessus, nappe dont la partie supérieure se trouve dans un terrain de perméabilité K_1 supérieure à celle K_2 des terrains inférieurs portant la nappe. Les épaisseurs de ces terrains sont supposées varier très peu dans le domaine d'action des puits. Supposons ces puits sans interaction l'un sur l'autre et se comportant donc comme si chacun d'eux existait seul.

A une certaine distance d'un puits supposé unique, le puits n'influencera plus guère la nappe et les vitesses de filtration dans chacune des couches K_1 et K_2 seront par conséquent parallèles à la pente des couches et d'autre part, ces vitesses seront, dans chaque couche, proportionnelle au K correspondant. A cette distance, la surface d'égale hauteur piézométrique est perpendiculaire à la pente générale. De plus, il n'y a pas de passage de liquide d'une couche à l'autre en dépit de la possibilité d'un tel passage.

Il résulte de ce qui précède que pour deux puits ayant des caractéristiques de pénétration différentes, mais ayant le même débit, la répartition de la provenance du débit entre les deux couches est indépendante du degré de pénétration du puits.

En d'autres termes, quand le régime permanent à potentiel de vitesses sera établi,

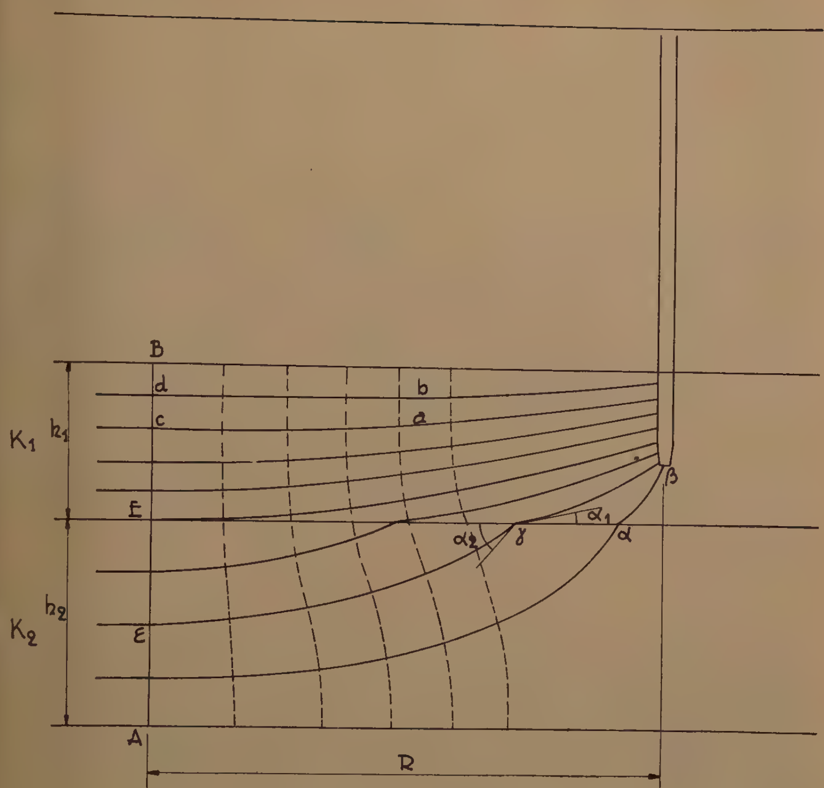


Fig. 5

tous les puits dont on tire le même débit recevront tous la même proportion d'eau en origine de la couche de perméabilité K, (peu salées et dures dans notre problème) et tous la même proportion en provenance de K_2.

Donc, à moins que la composition des eaux ne soit influencée par la nature du terrain au voisinage immédiat des puits, la composition des eaux arrivant aux puits sera la même, pourvu, répétons-le, que le mouvement permanent soit établi. Ceci demande un temps très long, théoriquement infini.

d) Nous avons admis plus haut (paragraphe 7 *b*) que même avant que ce mouvement permanent soit établi, les lignes de courant s'établissaient suivant des tracés identiques à ceux du mouvement permanent limite. Toutefois, tout en adoptant cette hypothèse, nous ne pouvons admettre que dès le début du pompage, un puits s'arrêtant au milieu de la couche K_1 par exemple, reçoive immédiatement le mélange indiqué ci-dessus en provenance des couches K_1 et K_2 (paragraphe 7 *c*). Il est notamment évident qu'au début du pompage, le puits ne recevra que de l'eau K_1 et il en sera ainsi aussi longtemps qu'une première particule en provenance de K_2 n'arrive pas au puits. A partir de ce moment la proportion d'eau K_2 arrivant au puits ira en augmentant et, dans notre cas, la salinité ira en augmentant tandis que la dureté

diminuera pour atteindre, après un temps très long, les caractéristiques indiqueés au 7 *c*).

Un puits plus profond, mais restant toujours dans la couche K_1, recevra évidemment plus rapidement les premières particules d'eau en provenance de K_2 et sa salinité augmentera plus rapidement, sa dureté décroissant plus vite en fonction du temps.

Quant à un puits atteignant la couche K_2, il recevra immédiatement de l'eau de cette couche dont la proportion augmentera cependant encore avec le temps.

Ceci nous permet d'expliquer une autre des anomalies constatées : la variation de la dureté des eaux de certains puits avec le temps. Le puits 1 de Heusden n'atteignant que la Maestrichtien très perméable (et de ce fait aux eaux encore relativement dures — voir 6 *c*) donne au début des pompages une eau peu saline et présentant encore quelque dureté (13°). Au contraire, les puits plus profonds des environs en dépit de leur situation parfois plus méridionale, donnent de suite des eaux plus salines et moins dures, du fait, avons-nous déjà expliqué, de l'arrivée immédiate de l'eau en provenance du Sénonien. Mais avec le temps, la situation se modifie au puits 1 de Heusden : après un certain temps, il reçoit à son tour de l'eau du Sénonien et la proportion de cette eau augmente avec le temps. Ce puits verra par conséquent la salinité de son eau croître après un certain temps (et sa dureté décroître). Et quand l'équilibre sera établi, la composition de l'eau de ce puits (à certaines influences locales près) sera celle des puits voisins qui atteignant le Sénonien ont immédiatement donné une eau à faible dureté. C'est ce que montre le puits n° 1 de Heusden où la dureté initiale de 13° F tombe en 7 ans à 5°6 F comme celle du puits voisin n° 2.

8. Il resterait à voir si on peut, dans une certaine mesure, suivre les modifications des compositions des eaux des puits avec le temps.

En utilisant les rappels théoriques du paragraphe 7 *b* (ce qui suppose l'approximation de la substitution des vitesses du mouvement permanent d'équilibre à celles mouvement non permanent réel) et en faisant abstraction de la légère pentes des couches, on peut construire pour un puits (par exemple le puits 1 de Heusden) une figure analogue à celle qui est schématisée par la figure 5. On suppose connues les perméabilités K_1 et K_2 ainsi que les épaisseurs h_1 et h_2 des couches et on étend la construction graphique rappelée jusqu'à une distance R où le mouvement peut être considéré comme non influencé par le puits.

Cette surface de rayon R et de hauteur $h_1 + h_2$ laisse passer le débit q du puits qui se subdivise en q_1 venant de la couche supérieure et q_2 venant de la couche inférieure.

Il est aisé de voir que :

$$q_1 = q\frac{h_1\,K_1}{h_1\,K_1 + h_2\,K_2} \quad \text{et} \quad q_2 = \frac{h_2\,K_2}{h_1\,K_1 + h_2\,K_2}$$

On peut en déduire les vitesse v_1 et v_2 dans chacune des deux couches à la distance R : il suffit de réduire les vitesses $\frac{q_1}{2\pi R h_1}$ et $\frac{q_2}{2\pi R h_2}$ par des coefficients tennat compte de ce que seuls les sections des tubes de transpiration des surfaces $2\pi R h_1$ et $2\pi R h_2$ sont utilisées pour le passage de l'eau. Ces coefficients ne peuvent se déterminer qu'avec une approximation assez grossière, en leur donnant les valeurs des porosités (les vitesses ainsi calculées sont trop faibles).

Connaissant les vitesses v_1 et v_2, il est aisé de calculer les vitesses en un point quelconque x, car le rapport $\frac{v_1}{v_x}$ vaut $\frac{ab}{cd}$.

Si on prend alors une ligne de courant telle que $\alpha\beta$, le temps t qu'une particule mettra à la parcourir vaudra :

$$\int_{\alpha}^{\beta} \frac{ds}{v}$$

cette intégrale pouvant se calculer par intégration graphique de la courbe $\frac{1}{v}$, les vitesses aux différents points de $\alpha\beta$.

Nous avons utilisé cette méthode pour un puite présentant des données assez représentatives du puits 1 de Heusden. Nous avons par exemple obtenu qu'une particule se trouvant à la séparation des deux couches (telle que γ par exemple) et distante de 100 m de l'axe du puits, met plus de deux ans pour arriver au puits.

Il en résulte qu'après ce temps, tout le débit en dessous de la ligne de courant $\delta\gamma\varepsilon$ vient de la couche inférieure, le reste vient de points qui à l'origine se trouvaient au-dessus de la ligne de séparation, donc provenaient de la couche supérieure. On en déduit qu'après le temps en question, le débit q_1 sera constitué :

a) du débit permanent q_1 de la couche supérieure;

b) d'un débit $q_2 \cdot \frac{E\varepsilon}{AE}$ venant encore de la couche supérieure;

c) d'un débit $q_2 \frac{\varepsilon A}{EA}$ venant de la couche inférieure.

9. Nous avouons ne pas être complètement satisfait de la méthode exposée sous le paragraphe 8. Elle est basée sur trop d'approximations : substitution des lignes de courant du mouvement permanent à celles du mouvement réel, non permanent, pente des couches supposée nulle, introduction d'une limite d'action R du puits, incertitude des valeurs des vitesses réelles par l'introduction de la porosité, sans parler de l'incertitude des valeurs de K_1 et de K_2 et de l'hypothèse de l'homogénéité chimique des eaux de chacune des couches. Nous considérons plutôt ce paragraphe 8 comme ayant un intérêt didactique en explicitant les considérations des paragraphes antérieurs dont les déductions qualitatives nous paraissent de quelque intérêt.

10. Ce qui précède nous porte á attirer l'attention des hydrologues surveillant ou effectuant des études de nappes, de préciser et de multiplier âutant qu'ils le peuvent les constatations. Cette remarque s'applique évidemment aux caractéristiques des couches portant les nappes, particulièrement à leur perméabilité et surtout aux variations possibles de cette perméabilité, mais elle s'étend peut-être plus encore à la détermination des fluctuations de la composition chimique des eaux dans le temps et à l'influence des modifications du débit des puits sur cette composition.

BIBLIOGRAPHIE

1. DELCOURT J. — Les eaux artésiennes salines du Bassin de Paris, de la Basse et de la Moyenne Belgique.
   Bull. Sté Belge Géol. T. XLVI - 1936.
   Id. — T. XLVII - 1937.
   Id. — T. XLVIII. - 1938.
2. H. SCHOELLER. — Les variations de la composition chimique de l'eau dans les nappes souterraines. — Assemblée d'Oslo. A.I.H.S. 1948.
   Id. — Les modifications de la composition chimique de l'eau dans une même nappe. — *Id.*

DECONTAMINATION DE LA NAPPE PHREATIQUE DE SKHIRAT ENVAHIE PAR DU KEROSENE

R. AMBROGGI, E. de GELIS et L. MONITION
Centre des Etudes Hydrogéologiques du Maroc

RÉSUMÉ

Le pipe-line qui véhicule le kérosène entre les bases américaines de Nouasseur et de Sidi-Slimane ne comportait pas, dès sa mise en place, de protection cathodique destinée à empêcher les corrosions par électrolyse susceptibles de se produire avec des courants électriques circulant dans le terrain et particulièrement intenses au droit des stations de chemin de fer électrifié.

Une fuite survenue à proximité du centre de Skhrirat a pollué en kérosène la nappe phréatique circulant dans les schistes altérés d'âge primaire. Cette contamination menaçait dangereusement le secteur côtier maraîcher dont l'irrigation se fait uniquement à partir des eaux souterraines.

— Le problème à résoudre consistait à :

a) Eviter l'extension de la pollution vers d'autres zones et particulièrement la zone côtière;

b) Assainir la nappe partout où elle était envahie par le kérosène.

— Deux procédés de décontamination ont été proposés :

a) Monter d'une part en série des pompes à membrane électromagnétique et « écrémer » la surface du puits pour recueillir un mélange contenant avec une partie d'eau tout le pétrole, tandis que d'autre part on pomperait l'eau contenue dans le puits pour créer ainsi une dépression conduisant le pétrole vers ce puits.

b) Placer des brûleurs spéciaux dont la caractéristique serait de ne comporter aucune pièce mécanique sujette à usure ou avarie. Ces brûleurs auraient également l'avantage de s'allumer en un instant depuis le sol, de se mettre d'eux-mêmes en veilleuse dès que le carburant se raréfierait et d'entrer à nouveau en pleine action lorsque l'épaisseur de carburant dépasserait quelques dizaines de millimètres, c'est-à-dire qu'ils seraient doués d'auto-régulation.

Les auteurs examinent ces deux projets et en évaluent le prix de revient.

En fait, la décontamination a été assurée sous le contrôle des auteurs par les services américains qui, pour des raisons non techniques qu'il ne nous appartient pas de discuter ici, ont effectué de simples pompages de longue durée.

SUMMARY

The pipe-line which conveys kerosene between the American Air Bases in Nouasseur and Sidi-Slimane had formerly no system of cathodic protection to avoid corrosions due the electric current spreading into the ground and particularly intense at the level of the electrified railroad stations.

A leakage occured near Skhrirat which polluted the underground waters circulating in the upper part of primary shales, menacing dangerously the cultivated coastal area which is irrigated only with these waters.

The problems to be solved were:

a) Avoid the extension of the pollution towards other areas and specially to the coastal area,

b) Purify the watertable everywhere it was invaded by kerosene.

Two processes have been proposed:

a) The first consists in using pumps with electromagnetic membranes to «skim» the surface of the water and pick up a mixture containing a part of water and all the petroleum in the well, another pump being then put in action to empty the well and create a depression conveying the petroleum to it.

b) A second solution would be to use special burners that have no mechanical parts liable to wear and damage, that would be lighted on the ground surface and lowered into the well, where they would burn the kerosene coming to the surface of the waters. This means that they would follow automatically by a self regulation device the thickness of the kerosene film.

The authors study both and estimate their costs.

In fact, these experiments were conducted, under the control of the authors, by the American Army Services which for untechnical reasons that are not to be discussed here performed only simple pumpings for long period.

La pose du pipe line destiné au transport du kérosène entre les bases américaines de Nouasseur et de Sidi-Slimane s'est effectuée durant le premier semestre 1952. Mais ce n'est qu'en 1954 que cette canalisation a été munie d'un système de protection cathodique permettant d'éviter les corrosions par les courants électriques circulant dans le terrain et particulièrement intenses au droit dessous-stations C. F. M. (Chemins de Fer du Maroc).

Divers essais effectués tantôt à l'aide d'eau, tantôt à l'aide de kérosène devaient révéler au début de l'année 1954 une fuite aux environs de Skhirat, à l'embranchement de la Route Principale Casablanca-Rabat et de la Route des Fonderies, et une autre au passage de l'Oued Ykem. Ces fuites ont été colmatées, mais cinq eucalyptus situés en bordure de la route ont aussitôt dépéri, prouvant à cet emplacement une diffusion assez large du pétrole dans le terrain.

Au mois de juin, la contamination affectait les puits I, II et III (voir plan hors texte), puis au mois d'août les puits IV et V. Bientôt le puits VI en cours d'exécution, rencontrait à son tour le pétrole.

La pollution menaçait alors dangereusement la zone côtière à vocation maraîchère dont l'irrigation se fait uniquement à partir des eaux souterraines.

Le Centre des Etudes Hydrogéologiques du Maroc chargé d'étudier ce problème s'est attaché à rechercher le mode de décontamination le plus économique, mais réunissant cependant le maximum de changes de succès.

* * *

I — Aperçu hydrogeologique

Le secteur considéré est constitué par un socle d'âge primaire inégalement érodé sur lequel se sont déposées des formations calcaréo-gréseuses du Plio-quaternaire.

La bordure côtière comprend des formations dunaires plus récentes superposées à l'ensemble

1°) Le substratum primaire comporte des schistes bleu ardoise dans lequel s'intercalent des bancs de quartzites d'âge viséen (carbonifère supérieur).

Le pendage général est subvertical E - NE.

2°) Les formations quaternaires sont constituées par des calcaires gréseux et dans la zone côtière par des dunes récentes.

L'observation de 47 points d'eau montre que dans le secteur de Skhirat la nappe aquifère circule toujours dans la partie supérieure des schistes (fig. 1) probablement selon des cheminements privilégiés à la faveur de zones plus fissurées ou plus altérées.— les formations calcarée-gréseuses de couverture ne permettant seulement qu'une bonne infiltration des eaux météoriques.

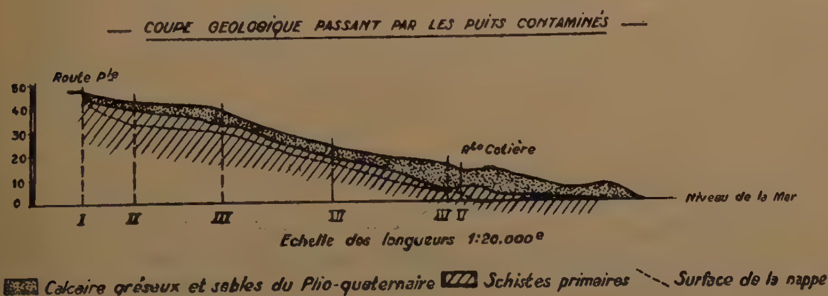


Fig. 1

Un nivellement de précision a été effectué. Tous les puits ont été soigneusement repérés et leur rattachement topographique a permis de tracer une carte phréatique précise.

Cette carte est jointe en hors-texte, superposée à la photographie aérienne de la région considérée.

Les résultats des échantillons d'eau prélevés, analysés au laboratoire de la Division des Mines du Ministère de l'Economie Nationale, et reportés sur diagramme logarithmique (fig. 2) montrent, malgré une certaine diversité de composition chimique, l'appartenance de ces eaux à une même famille.

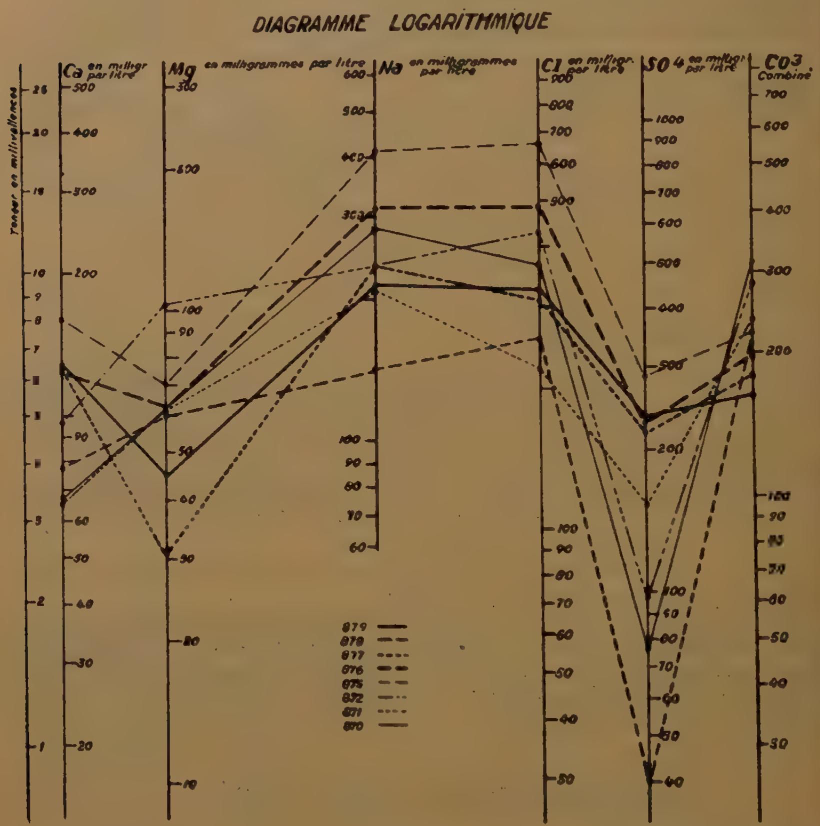


Fig. 2

II — Envahissement de la nappe aquifere par le kerosene

Le comportement du pétrole et de l'eau dans le terrain est complexe. En effet:

— Ces fluides n'ont pas la même densité; aussi le pétrole flottera sur la nappe aquifère, tout au moins tant que ne se produiront pas des infiltrations verticales d'eau de pluie.

— Ils n'ont pas la même viscosité et de ce fait, à gradient égal, ne se déplaceront pas à la même vitesse.

— Le pétrole est insoluble dans l'eau mais peut facilement y entrer en émulsion. Cette émulsion est très stable et peut se faire jusqu'à un taux voisin de 5/1.000.

— Le pétrole est très facilement adsorbé par les terrains.

Dans cet état, il ne peut être extrait par épuisement mais risque d'être libéré partiellement à la suite d'un lavage dû à l'infiltration des eaux météoriques.

— Enfin, il n'a pas la même tension superficielle que l'eau et pourra rompre l'équilibre de la frange capillaire qui surmonte normalement une nappe aquifère en milieu poreux.

Des pompages intensifs commencèrent à être exécutés dans les puits contaminés, considérés à juste titre comme « abcès de fixation ». Le but de ces opérations urgentes de pompages était de préserver le secteur maraîcher de la bordure océanique.

La quantité [1] de kérosène prélevée au cours des pompages (effectués par les Services américains) dans les 6 puits contaminés entre le 9 septembre et le 30 novembre 1954 a pu être évaluée avec une précision suffisante. Elle s'élève à 442 m³ environ. Cette valeur a été établie en partant des épaisseurs de kérosène mesurées dans les puits avant chacun des pompages. Cette épaisseur était la même sur toute la surface libre à l'intérieur du puits. Le pompage ne durant que quelques heures au maximum, les apports pendant ce temps devaient être négligeables.

Le rendement des pompages a décru très rapidement, ce qui a pu être traduit par la courbe représentative (fig. 3), établie sur les mois de septembre à décembre 1954.

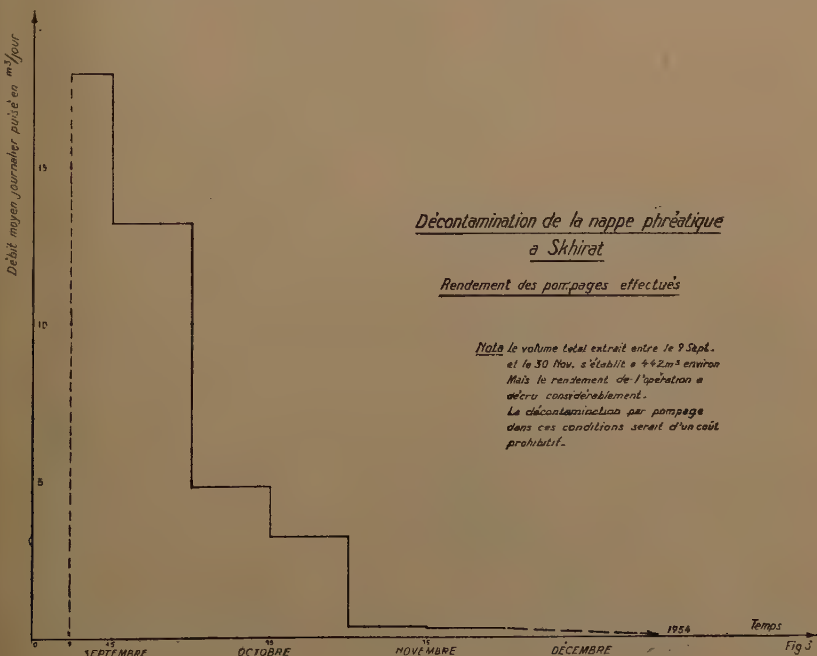


Fig. 3

[1] La quantité échappée du pipe n'a jamais pu être connue, même approximativement.

Le kérosène exhauré à l'aide de pompe à air comprimé et recueilli dans des citernes de 20 m^3 de capacité, était emmené à Nouasseur, soit à 95 km environ de Skhirat où il était brûlé.

III — Procèdes de decontamination

Diverses entreprises émirent des propositions pour exécuter les travaux nécessaires de décontamination.

Le principe de l'opération était toujours le même :

— Eviter que la contamination ne s'étende à d'autres puits et notamment ne progresse en direction du secteur maraîcher.

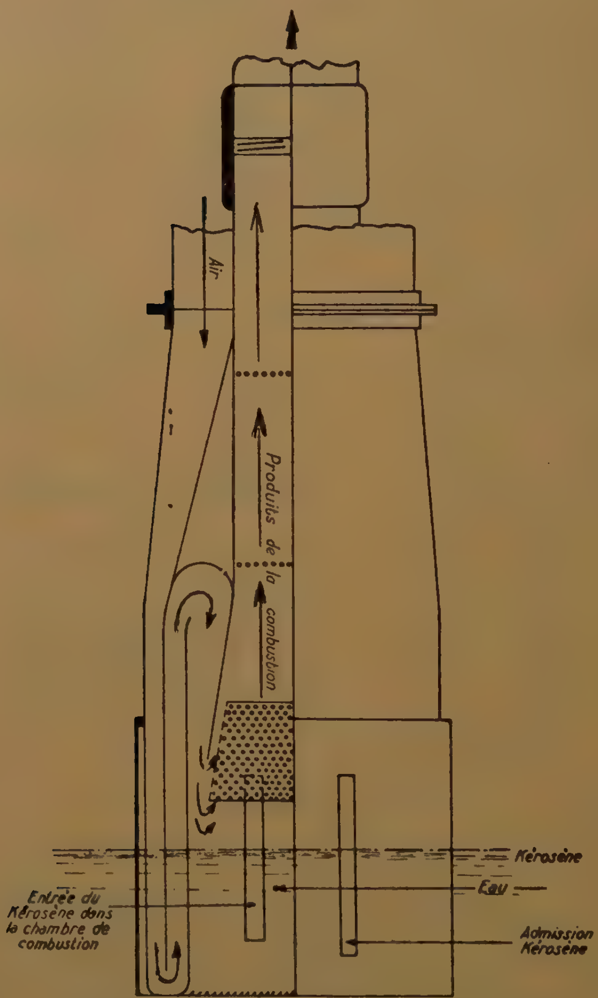


Fig. 4

— Assainir la nappe partout où elle était envahie par le pétrole.

Nous avions précédemment fait deux propositions pour atteindre ces objectifs :

— Créer un front de rabattement en contrebas du dernier puits contaminé.

— Pomper dans les puits pollués situés à l'amont de ce barrage pour abréger la durée des pompages nécessaires à l'aval.

L'expérience des premiers mois a montré que les puits IV et V formaient à eux seuls un front de rabattement et que le pompage effectué dans ceux-ci avait stoppé la progression du kérosène vers l'aval (secteur maraîcher). Mais cette expérience a également prouvé que les pompages avaient un rendement dégressif avec le temps et qu'ils étaient d'un prix de revient prohibitif.

Il est apparu toutefois indispensable, en attendant de trouver une nouvelle solution, de continuer de pomper dans les puits IV et V afin que le pétrole ne puisse reprendre sa progression vers l'aval.

Les entreprises s'efforcèrent alors de diminuer le coût des opérations, en supprimant les transports du kérosène jusqu'au lieu où il était brûlé.

Deux procédés ont ét présentés :

— Le premier par la Société Sondage, Injections, Forages (S. I. F.) consiste à monter en série des pompes à membranes électromagnétiques et à « écrémer » la surface du puits pour recueillir un mélange contenant une partie d'eau et tout le pétrole, tandis que l'on pompe dans le puits (créant ainsi une dépression orientant les pétrole vers le puits) une eau pratiquement exempte de pétrole et que l'on peut ainsi vider sur le terrain ou dans le caniveau de la route.

— Le second procédé a été présenté par la Société GROSPAS et consiste en brûleur spéciaux (fig. 4) qui ont l'avantage de ne comporter aucune pièce mécanique sujette à usure ou avarie. Ces brûleurs ont également l'avantage de s'allumer en un instant depuis le sol, de se mettre d'eux-mêmes en veilleuse dès que le carburant se raréfie et d'entrer à nouveau en pleine action lorsque l'épaisseur du carburant dépasse quelques dizièmes de millimètres; en un mot, ils sont doués d'auto-régulation.

Avec ce second procédé d'élimination du kérosène comme avec le premier, il faut pomper l'eau pour créer la dépression nécessaire qui doit orienter le pétrole vers le puits.

Du point de vue purement technique les deux procédés d'élimination du pétrole sont comparables. Tous deux sont susceptibles d'enlever 30 à 40 litres de kérosène par heure et par engin; tous deux nécessitent une surveillance et tous deux exigent un pompage d'eau complémentaire qui leur assurera une efficacité égale.

L'entreprise S. I. F. avait pensé pouvoir éliminer les sujetions de pompage d'eau en créant en aval du dernier puits contaminé, un barrage constitué d'un très grand nombre d'engins placés à quelques mètres les uns des autres, et qui ôterait le pétrole de la nappe au fur et à mesure de sa venue.

Cette façon de procéder pouvait être appliquée avec les brûleurs GROSPAS, exactement au même titre.

Les prix de revient des travaux effectués suivant l'une ou l'autre méthode et par chacune des entreprises font l'objet du tableau comparatif ci-après.

Dans les deux cas a été évalué le coût des travaux qu'il est indispensable d'exécuter si l'on ne veut pas voir le pétrole reprendre la direction du secteur maraîcher.

Mais évidemment le temps nécessaire pour une décontamination totale ne pouvait être estimé, car il était impossible de connaître la quantité de kérosène répandu dans le sous-sol.

Les mesures de l'épaisseur du kérosène sont encore effectuées à l'heure actuelle et des pompages d'épuisement total des puits contaminés sont exécutés le cas échéant. Les derniers travaux de pompage ont eu lieu le 12 février 1957.

Le pétrole subsiste et les observations du 10 avril 1957 ont montré que les puits contaminés étaient tous recouverts d'une pellicule de kérosène.

C.E.H
CARTE PHREATIQUE
DE LA REGION DE SKHIRAT
Echelle 0 1km
Fichier Inventaire des Ressources en Eau du

Fig. 5

TABLEAU COMPARATIF DES PRIX (1)

1ère Solution

(Avec six centres d'élimination du pétrole; un sur chacun des puits actuellement contaminés et pompage d'eau assurant l'efficacité du procédé)

	S. I. F.	GROSPAS
— Montage dans les 6 puits actuellement contaminés, location et démontage en fin de travaux des appareils destinés à l'extraction de 30 à 40 litres de kérosène par heure et par puits (compte tenu des reprises de matériel en fin de travaux)	360.000	1.358.000
— Prix journalier pour mise à disposition du personnel pour la surveillance et l'entretien de ces engins pendant leur fonctionnement :		
Les 2 premiers mois	18.000	36.000
Les mois suivants	18.000	24.000
— Prix journalier pour pompage auxiliaire d'eau tenant compte de la location des pompes et du personnel ncéessaire à leur conduite estimé à	100.000	
Total pour : 4 mois	14.520.000	16.958.000
8 mois	28.680.000	31.838.000
1 an	42.840.000	46.718.000

2ème Solution

(Avec 100 centres d'élimination du pétrole sur une ligne de 100 forages à créer à 4 m les uns des autres en contrebas du dernier puits contaminé)

	S. I. F.	GROSPAS
— Exécution de 1000 m de forage en diamètre convenable pour y poser un appareil capable d'extraire 30 à 40 litres de kérosène par heure	11.000.000	10.000.000
— Montage dans ces 100 sondages et démontage en fin de travaux de 100 appareils destinés à extraire le kérosène	6.000.000	26.000.000
— Prix journalier pour mise à disposition du personnel pour l'entretien et la surveillance de ces engins pendant leur fonctionnement :		
Les 2 premiers mois	100.000	237.000
Les mois suivants	100.000	157.000
Total pour : 4 mois	39.000.000	59.000.000
8 mois	51.000.000	78.400.000
1 an	63.000.000	97.200.000

(1) Exprimés en Francs Marocains 1955.

POLLUTION OF GROUND WATERS BY OIL-FIELD WASTES IN SOUTHERN CALIFORNIA

JOHN F. MANN, Jr. & RICHARD O. STONE
Department of Geology
The University of Southern California Los Angeles, California

Abstract

Oil has been pumped for more than 90 years in southern California, which for many decades has been one of the important oil-producing areas in the United States. In conjunction with normal oil-field operations, there are acquired numerous materials which are generally considered as wastes. These include (1) highly saline waters produced with the oil, (2) drilling mud, (3) oily substances which can not be treated economically and (4) refinery sludges. In general, these have been disposed of in the easiest and most economical manner; the methods employed have been the following: (1)discharge directly to the ocean; (2) discharge to the nearest drainage course; (3) discharge to a nearby unlined sump; (4) removal to a convenient pre-existing depression such as a gravel pit; (5) discharge into a nearby abandoned water well. Many of the sumps are underlain by permeable materials and the waste fluids have traveled freely to the water table. Often the discharge is to sumps or canyons located on impermeable rocks, but commonly there is overflow and the saline fluids reach the important alluvial aquifers which are found in almost all of the larger stream valleys. Recent geologic studies have outlined the areas of actual or potential concern and called attention to the dubious disposal methods: steps are now being taken to correct these situations. Unfortunately, the cost of the remedy is so great as to make some of the oil operations unprofitable. A helpful development has been the injection of brine through wells as a means of secondary recovery of the oil.

Introduction

The area that will be discussed includes a large portion of the oil-producing section of coastal southern California, particularly Ventura, Los Angeles, and Orange Counties (Figure 1). There is a long history of oil production starting in 1866, although most of the production has been obtained in the last few decades. The total cumulative production amounts to almost 5.5 billion barrels of oil, and along with the oil about 2 billion barrels of brine. The indiscriminate disposal of this brine, as well as numerous other substances usually resulting from normal oil-producing and oil-refining activities, has resulted in a serious and widespread pollution of ground waters.

Geologic Setting

Coastal southern California, from a geologic standpoint, is relatively young. The basement rocks consist of plutonic and metamorphic rocks of Mesozoic age. There is a thick sequence of unmetamorphosed marine and continental Tertiary sedimentary rocks from which, especially those of Miocene and Pliocene age, the oil is produced. Fresh ground waters are found mainly in the youngest rocks, ranging in age from Late Pliocene to Recent. Physiographically, the area discussed (Fig. 2) consists of two coastal plains separated by and enclosed by hilly areas of exposed Tertiary and Mesozoic rocks. Most of the ground water is pumped from the coastal plains areas where the fresh ground waters (extending in places to depths of several thousand feet) overlie highly productive oil fields. Most of the fresh ground waters


N
OIL FIELDS
IN SOUTHERN CALIFORNIA
0
50
MILES

Fig. 1

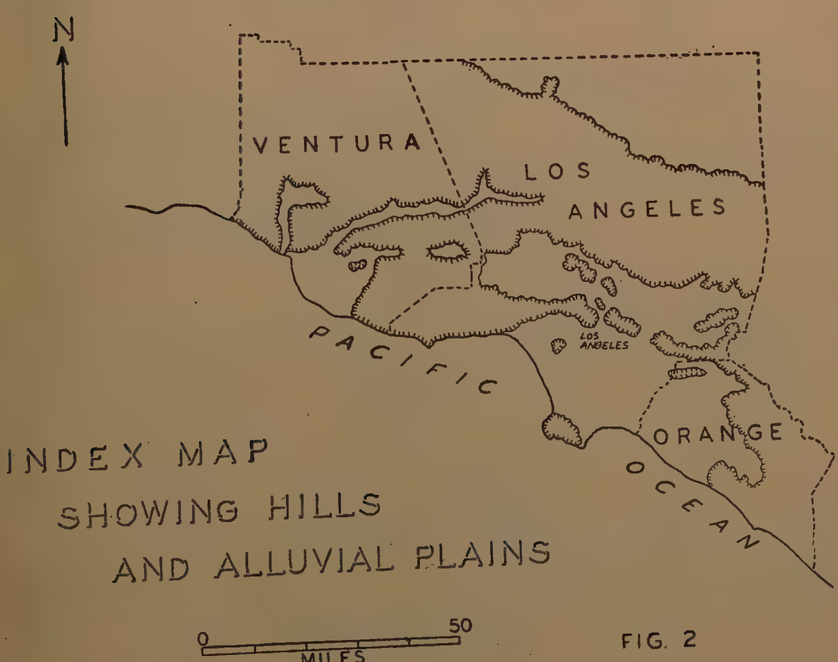

N
VENTURA
LOS
ANGELES
LOS ANGELES
PACIFIC
OCEAN
ORANGE
INDEX MAP
SHOWING HILLS
AND ALLUVIAL PLAINS
0
50
MILES

FIG. 2

underlying the coastal plains are in marine Late Pliocene and Early Pleistocene deposits which have been folded and faulted by the important Middle Pleistocene diastrophism. These aquifers, initially containing sea water, have had the connate waters flushed out by fresh waters. Shallower ground waters (most of them natively fresh) are found in Late Pleistocene and Recent continental deposits. A generalized stratigraphic section of the freshwater-bearing layers beneath the coastal plains is shown in Table 1. Extending inland from the coastal plains are numerous tributary basins and valleys, filled for the most part with Late Pleistocene and Recent alluvial deposits which constitute the most important aquifers.

TABLE 1

Generalized stratigraphic section
of the fresh-water aquifers beneath the coastal plains of southern California

Ground Surface
Recent sands and gravels Perched or semi-perched waters Natively fresh or saline
Silts and clays Confining layer Locally absent
Recent sands and gravels Waters generally artesian (originally) Waters natively fresh
Silts and clays Confining layer Locally absent
Late Pleistocene sands and gravels Several lenses or zones Waters generally artesian (originally) Waters natively fresh or saline
Silts and shales Confining layer Locally absent
Thick sands and gravels Late Pliocene and Early Pleistocene Waters generally artesian Waters natively fresh x x x x x x x x x x x Saline connate waters (Including oil-field brines)

Types of Oil-field Wastes

Brines

The chemical quality of the waters produced with the oil in southern California shows a wide range. In the Conejo Oil Field, where the oil is pumped from fractured basalts, the accompanying water contains as little as 612 parts per million total dissolved solids and is potable. On the other extreme are the numerous fields producing a brine which has a total dissolved solids content approaching (or even exceeding) that of normal sea water. Although most of the waters are of a sodium-chloride type, there are waters representative of sodium-bicarbonate, sodium-sulfate, and even calcium-chloride types. Most of the waters are brines, with a total dissolved solids content in excess of 15,000 parts per million, and a boron content greater than 50 parts per million. The chief deleterious effects of oil-field brine pollution, in addition to increasing total dissolved solids, are to increase the sodium percentage and the boron content, both detrimental in agricultural waters.

Produced Hydrocarbons

The oils produced are mainly of high specific gravity and have an asphaltic base. Prior to the disposal of the brines an attempt is made to recover all the oil in settling tanks, often after treatment with a demulsifying agent. The brine discharged to waste is generally free of oil, although it may contain minute, but significant, amounts of dissolved hydrocarbons and other substances which are potential ground-water pollutants. In conjunction with production activities, other hydrocarbon wastes are accumulated from the cleaning of tubing in wells, and from the cleaning of storage tanks and other equipment.

Drilling Mud Wastes

The usual bentonitic mud perhaps includes no potential ground-water pollutants, but the advances in drilling-mud technology over the past 20 years have brought with them a great host of substances which are potential pollutants. Recent developments include oil-base and oil-emulsion muds, and numerous organic and inorganic conditioning chemicals, of which some, even in minute quanties, might render a fresh ground water unusable.

Refinery Sludges

From oil refineries come numerous products derived from complex chemical processes in which large volumes of chemical reagents are used. The spent chemical–reagents, along with unusable parts of the crude oil, represent a waste product whose large volume and toxicity present a difficult disposal problem.

Methods of Disposal

Essentially all early waste disposal in the oil fields was accomplished in the simplest and most economical manner. Little thought was given to the possible consequences of such disposal. Such early indiscriminate practices were not confined to the oil industry, but were pursued with equal abandon in almost all industries.

Release to Natural Drainage Channels

Following initial settling in steel tanks, the oil-field brines may be piped for further settling to a sump where the remaining oil is skimmed off. If the soil beneath the sump is permeable, the brine will percolate into the ground; if impermeable, the sump will overflow. Generally the sump is located in or near a natural drainage channel so the overflowing brine will easily flow away.

Release to Natural Depressions

If there is no drainage course nearby, the effluent from the skimming sump may be diverted into a natural depression from which the brine evaporates and/or percolates to the underground.

Release or Removal to Artificial Excavations

After skimming, the sump effluent may be diverted to an artificial drainage ditch or flood control channel. Perhaps the commonest disposal point is the mud pit which had been used during the drilling of the rotary hole. These convenient mud pits become the receptacles for almost anything in the vicinity for which there is no further use. Often, special sumps are excavated near the settling tanks, and they are placed where the brine remaining in the bottom of the tanks can conveniently be drained. Large nearby gravel pits were especially sought-after disposal areas; to these the wastes (usually other than the brines) could be trucked with a short haul. In one oil field where the permeability of the soil was rather low, cesspools were dug especially for the disposal of the saline wastes. In another oil field large volumes of brine were diverted to a crater developed where a well had blown out and burned.

Release to Ocean Outfalls

In some of the oil fields located close ot the ocean front, it was found convenient to pipe the brines to the beach or tidewater, even as much as 30 years ago. As awareness of the consequences of ground-water pollution grew, more elaborate systems were constructed. In some of the inner coastal plain fields, the oil operators contracted with public agencies to pipe the brines to sanitary sewers which reached the ocean. In several areas a brine collecting system was built to connect to a pipeline laid especially for the purpose of conveying the brines to the ocean, as much as 15 miles away. In local areas incomplete removal of oil from the brines piped to the ocean has resulted in serious beach pollution.

Piping to Iodine Extraction Plants

Certain of the oil fields in coastal Los Angeles and Orange Counties produce brines which contain appreciable quantities of iodine. Three plants, constructed especially for the purpose of extracting this iodine, currently handle a large part of the brine effluent of several of the larger fields.

Injection into Wells

Injection of brines into wells is a relatively recent practice for which there are two basic objectives: (1) to dispose of the brines, and (2) to implement a secondary recovery operation. The brines now are injected into the same geologic formation from which they were derived, or into another formation deep enough to eliminate

the possibility of polluting fresh ground waters. An early practice was to let the brines flow into unused water wells.

Pollution of Ground Waters

Direct Percolation to the Water Table

As the early methods of brine disposal involved discharging them to the nearest depression or drainage channel, it is not surprising to learn that the most direct pollution of fresh ground waters has occurred where the oil fields have surficial materials of alluvium, such as on the coastal plains and in the larger valleys. The Ventura Avenue Oil Field, whose anticlinal axis trends east, is traversed by the broad alluviated valley of the south-flowing Ventura River. Intensive brine disposal on this permeable alluvial surface has made unusable the ground waters from the ocean inland for a distance of more than five miles. On the coastal plains, where the stratigraphy of the freshwater zones is more complex (Table 1), the pollution occurs in those zones (usually the Recent deposits) which are in free hydraulic continuity with the ground surface.

If the various channels, depressions, and sumps to which the brines are released are underlain by permeable deposits, a large proportion of the brines will percolate downward and reach the water table. It has been maintained vigorously at times that these sumps function exclusively as evaporation basins. Although evaporation is undoubtedly of some importance, it is not the chief mode of fluid disappearance unless the sump is large and the bottom relatively impermeable. A recent investigation by the California Division of Water Resources in northern Orange County was undertaken to shed some light on this problem (Ref. 3). Adequate climatological records show mean annual precipitation in Orange County to range from 12 inches along the coast to 14 inches inland. Mean annual evaporation ranges from 44 inches along the coast to 51 inches inland. With these data, and knowing the brine inflow to the sump, the amount leaving as evaporation can easily be calculated. In an unlined earthen sump excavated in a typical soil, it was found that brine penetration rates started at 4.40 feet per day and decreased to about 0.15 feet per day after 75 days of operation. Inasmuch as used drilling mud was claimed to be an effective sealant for brine sumps, percolation tests were conducted in a sump lined with drilling mud. Mean percolation rates were found to be about 0.015 feet per day. Much higher rates were observed where the sump was intermittently filled and the mud was allowed to desiccate periodically. Even where the brine percolation rate was as low as 0.015 feet per day, it was found that only half the volume of the brine was lost to evaporation. However, it is significant to note that even though half the volume of the brine is evaporated, the salts remain behind and percolate downward in the more concentrated brine. If the salts are temporarily deposited in the sump, they will be carried downward during periods of heavy rainfall.

Indirect Pollution of Recent Alluvium

Many of the inland oil fields are in the hilly sections where Tertiary or Lower Pleistocene rocks are the surficial materials. Skimming sumps are commonly constructed by building an earth embankment in a canyon. If the brine is on permeable materials, much of the brine may be lost by percolation, but ground-water pollution results only if the absorbing formation is an aquifer. More often the sump is on impermeable rocks and the brine overflows down the canyon to percolate into the alluvium of the main stream. Failure of the earth embankment may release a

large volume of brine and oil which will also reach the Recent alluvium of the main stream.

In some of the smaller inland fields, the initiation of a brine injection secondary recovery operation may result in a flow of brine from inactive wells on nearby leases. The brine either percolates downward or flows on the ground surface in a completely uncontrolled manner.

Pollution of Deeper Zones

Least subject to oil-field brine pollution are the Upper Pliocene-Lower Pleistocene aquifers (Table 1) except where they are in free hydraulic connection with the ground surface. In most places these aquifers are overlain by one or more confining layers. The Recent deposits, which are most easily polluted, also are characterized by local areas in which the native waters were highly saline. Likewise in some parts of the Upper Pleistocene deposits, the waters were natively saline. Thus the thick and important Upper Pliocene-Lower Pleistocene aquifers are in many places overlain by natively saline or deteriorated waters, and everywhere underlain by saline connate waters. Adequate measures for protection against pollution must consider pollutants moving from both above and below. In California the regulations covering the casing and abandoning of oil wells are quite rigid, and the possibilities of pollution from below are probably small. Therefore, the chief source of pollutants is above. Water wells perforated in several zones offer one of the most convenient conduits through which the saline semi-perched waters move downward. Lack of adequate regulations regarding the abandonment of water wells has resulted in many being left unfilled, then covered over and permanently lost. It was estimated by the officials of one small coastal town near which the shallow waters are deteriorated, that there are probably fifty abandoned and lost water wells through which downhole pollution might be taking place.

Recognizing Oil-field Wastes as Pollutants

Pollution of water wells by oil-field wastes has in some instances been claimed without justification, perhaps because of the large organizations which could thereby be held responsible for damages. In order to conclude that oil-field wastes (or any other type of liquid waste) is responsible for a specific example of ground-water pollution, it should be established that

1. the geologic evidence supports probable hydraulic continuity from the point of waste disposal to the area of pollution,
2. hydraulic gradients will (or did) permit the necessary fluid movements,
3. the period of years involved was ample, considering the hydraulic gradient, the path traversed, and the permeabilities of the lithologic units in that path,
4. the chemical quality of the deteriorated water indicates it is a mixture of the fresh water and the polluting fluid, making allowances for expectable chemical modifications.

Items 1. and 2. can be resolved by geologic field studies and test hole information, along with recent and historic water-level data. The rate of travel of pollution is a more difficult problem which may not be susceptible of direct measurement. For the Los Angeles area, where industrial waste pollution has been recorded in Recent and Pleistocene sandy aquifers, the following data are offered:

Years	Distance travelled	Feet/year	Reference
1905-1918	2600 feet	200	9
1918-1925	2000 feet	286	9
1925-1928	2400 feet	800	9
1928-1942	7700 feet	550	9
1941-1945	2500 feet	625	6

A particularly complex problem was excellently handled by the Ground Water Branch of the United States Geological Survey in two reports covering the Los Angeles plain ([7,8]). Three sources of potential saline pollutants were studied and the responsible pollutant was indicated for many areas of deteriorated waters. Natively saline waters were in many places chemically distinct, but setting up chemical criteria to distinguish sea-water pollution from oil-field brine pollution was much more difficult. Normal sea water and the oil-field brines are quite different chemically, but when sea water intrudes fresh-water zones it undergoes extensive chemical changes; ratios of major ionic constituents can no longer be used effectively. It was found that minor elements could be used, although unfortunately these are not often found on reports of chemical analysis. Barium and iodide are relatively abundant in the connate waters, but virtually absent from normal sea water; borate, and to some extent bromide, are several times as plentiful in connate water. Other minor constituents may be effective criteria for the recognition of oil-field brine pollution in other parts of the world where the connate waters may be of a somewhat different chemical character.

Water Well Pollution by Refinery Sludge

A very interesting case of ground-water pollution was observed recently in a well near the town of Yorba Linda, Orange County. A discussion of this problem was first presented in a report to the Directors of the Orange County Water District by Mr. Dion L. Gardner, through whose courtesy the details are presented in this paper.

The Anderson well was drilled into the alluvium of the Santa Ana River where the alluvium widens as the river leaves Santa Ana Canyon. The well is an old one, drilled originally to 90 feet, but now probably no more than 67 feet deep. For many years the well produced domestic water of good chemical quality. Suddenly, on about October 9, 1945, the water became undrinkable and remained so for the rest of the year. The water was drinkable from about January to June of 1946, and the quality was bad from June to August of 1946. It was good from late August to December 2, 1946, bad until January 10, 1947, and good until July 12, 1947. As part of the investigative program several test wells were drilled and numerous chemical analyses were made. The pollutants included hydrocarbons and reducible sulfur, common constituents of acid refinery sludge. This confirmed earlier suspicions that the source of pollution lay about 1700 feet north in a gravel pit which had been used for the disposal of acid sludge and drilling mud. The gravel pit was excavated in a stream terrace cut on slightly folded Pleistocene alluvial deposits. In the late summer months when there is heavy pumping from the alluvium of the Santa Ana River, the water-table contours are markedly concave in the downstream direction. At such times, water is able to seep slowly from the terrace gravels into the alluvium (fig. 3). In test drilling, a patch of polluted ground water was discovered in the alluvium between the well and the dump, and when the water table slopes southwest, this polluted water moves into the well.

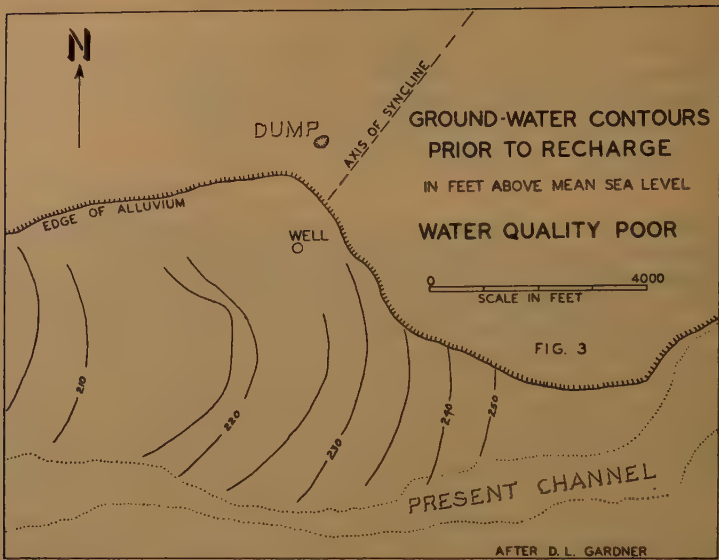


FIG. 3

During the winter, when there is flow in the river, there is strong ground-water recharge, and the pollutants are flushed out of the alluvium in the vicinity of the well (fig. 4). The quality of the water in the well improves approximately one month after the river starts to flow.

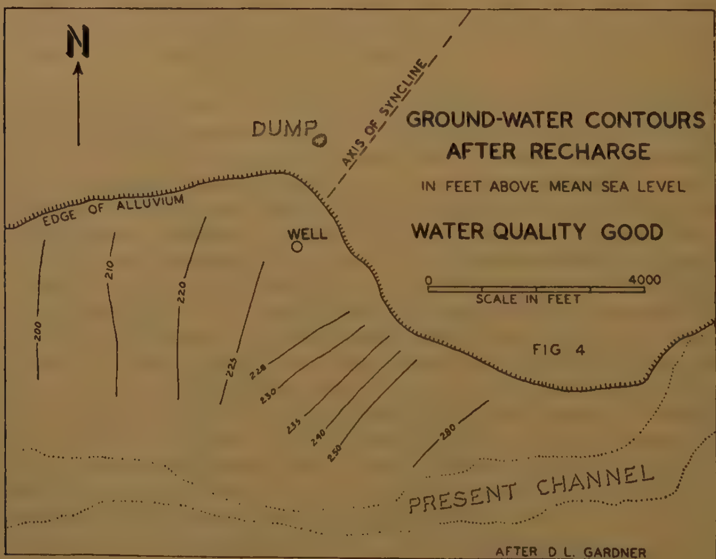


FIG 4

Magnitude of Present and Future Pollution

Of the estimated 2 billion barrels of brine which have been produced along with the oil in this portion of southern California, a very substantial percentage has percolated underground where it has polluted natively fresh waters or markedly increased the salinity of the natively poor waters. Over a total of several square miles, fresh-water aquifers have been deteriorated exclusively or largely by oil-field brines. Included among the most serious areas are the Ventura Avenue, Torrance, Long Beach, and Huntington Beach Oil Fields. It was not until 1949 that California had the legislation, investigative organization, and injunctive powers to stop water-polluting practices. Since 1949 a great improvement has taken place. But discontinuing the addition of pollutants to the ground water does not end the ground-water pollution problem. There is ample justification to conclude that the ground-water pollution which has occurred is permanent. We have, then, the picture of large areas of polluted waters spreading slowly and incessantly throughout the deteriorated zones, always prepared to take advantage of hydraulic gradients and improperly abandoned wells to spread the pollutants to other zones. Although the future may hold adequate and economical solutions, for the present it is difficult to avoid the conclusion that the ground-water pollution will continue to worsen for many years to come.

REFERENCES

(1) Brown, W. M., 1935. Industrial pollution of ground water; *Water Works Engineering*, Feb. 20, pp. 171-177.

(2) California Division of Water Resources, 1954. Survey of oil industry wastes in Orange County; a report to Santa Ana Regional Water Pollution Control Board (No. 8), 74 pp. and illustrations, mimeographed.

(3) California Division of Water Resources, 1954. Oil-field brine penetration investigation, Orange County; a report to Santa Ana Regional Water Pollution Control Board (No. 8), 61 pp. and illustrations, mimmeographed.

(4) California Division of Water Resources, 1954. Ventura County oil waste investigation; a report to Los Angeles Regional Water Pollution Control Board (No. 4), 89 pp. and illustrations, mimeographed.

(5) Dickey, R. F., 1949. Report of the interim fact-finding committee on water pollution; Published by the Assembly of the State of California.

(6) Gardner, D. L., 1947. Yorba incident, Anderson well contamination, Orange County, California; report to Orange County Water District, unpublished.

(7) Piper, A. M., Garrett, A. A., and others, 1953. Native and contaminated ground waters in the Long Beach-Santa Ana area, California; *United States Geological Survey Water Supply Paper* 1136.

(8) Poland, J. F., Garrett, A. A., and Sinnott, Allen, 1948. Geology, hydrology, and chemical character of the ground waters in the Torrance-Santa Monica area, Los Angeles County, California; *United States Geological Survey mimeographed report*, 472 pp. and illustrations.

(9) —, 1951. Industrial waste pollution of water wells in the southeast portion of metropolitan Los Angeles; report to Regional Water Pollution Control Board No. 4, Los Angeles, California, 15 pp. and maps, mimeographed.

(10) —, 1953. Report on the Athens area industrial waste survey, Los Angeles County, California; Los Angeles Regional Water Pollution Control Board (No. 4), 12 pp. and maps, mimeographed.

(11) —, 1954. Report on the Torrance area industrial waste survey, Los Angeles County, California; Los Angeles Regional Water Pollution Control Board (No. 4), 29 pp. and maps, mimeographed.

POSSIBILITE DE PRELEVEMENT D'EAU DOUCE DES NAPPES SOUTENUES PAR DES EAUX SAUMATRES

Dr. Ing. L. ZORZI

RÉSUMÉ

On considère les rapports d'équilibre entre les eaux douces constituant une nappe fluente dans une formation rocheuse fissurée et les eaux de mer qui sont en contact avec celle-la, dans le but d'établir les limites d'un prélèvement d'eau destinée à l'irrigation.

AVANT PROPOS

Sur les zones du littoral où les nappes souterraines découlent sur une formation poreuse et fissurée qui s'étend jusqu'au dessous du niveau de la mer, les eaux douces qui forment la nappe flottent au-dessus des eaux salées de la mer qui envahissent, en profondeur, les dites formations : il s'agit d'un équilibre dynamique qui, outre que satisfaire les lois bien connues qui règlent l'équilibre entre les liquides de différente densité, est influencé par divers facteurs dépendant des spéciales conditions locales telles, par exemple, la perméabilité de la formation dans laquelle s'écoule la nappe, ainsi que le volume et la distribution, dans le temps, des écoulements.

La possibilité d'effectuer un prélèvement d'eau douce et son importance dépend des caractéristiques de cet équilibre : par conséquent la question des pompages dans les zones du littoral représente un problème de base commune dans les différentes situations locales sur lesquelles cependant agissent des facteurs différents qui dépendent des variations des conditions géo-hydrologiques.

Etant donné que, selon les cas, les méthodes d'enquête et d'analyse peuvent être diverses, il est intéressant de connaître non seulement les études de caractère théorique qui traitent ce problème en général ou bien sous un aspect particulier, mais aussi les résultats des enquêtes effectuées dans des conditions géo-hydrologiques particulières. pour des fins pratiques spéciales; ceci, en général, même si les enquêtes de ce genre sont nécessairement approximatives, incomplètes et souvent scientifiquement peu rigoureuses. En effet, c'est dans les recherches effectuées dans la complexité de l'ambiant naturel qu'on peut mettre en évidence et d'une façon exacte le jeu des facteurs qui ont une influence sur l'hydrologie souterraine.

En suivant cette idée nous citons ci-après les recherches effectuées par l'Office d'Irrigation des Pouilles et de la Lucanie (Ente Irrigazione di Puglia e Lucania) financié par la Caisse du Midi, dans le but de déterminer les caractéristiques de la nappe « carstique » coulant dans les calcaires fissurés, qui constituent le sol de base de la région des Pouilles, pour s'assurer de la possibilité d'une exploitation pour l'irrigation de ces eaux qui représentent une des plus importantes ressources hydrauliques du pays.

Cette recherche, dont le succès permettrait d'assurer l'irrigation de 30-40.000 hectares et qui intéresse par conséquent l'economie agricole de toute la Région, a dû affronter les problèmes délicats et complexes liés au prélèvement de l'eau sur les zones du littoral : en effet le territoire en question s'étend entre la mer Adriatique et la mer Ionienne et la plus grande partie de la superficie intéressée à l'irrigation par les eaux de la nappe carstique (400.000 ha env.) est justement celle comprise entre ces deux mers (fig. 1).

Fig. 1

La recherche a été effectuée très soigneusement en utilisant de tous les moyens à la disposition de la technique moderne : plus de 270 forages ont été effectués (pour un total de 30.000 m) en faisant des essais de prélèvement dans le but d'établir les caractéristiques de qualité et de quantité de la nappe en divers points; cette recherche directe a été complétée par des relèvements géophysiques (par le système électrique et gravimétrique), par des relèvements géologiques sur les lieux, par le recensement de puits existants et enfin par des observations sur les sources du littoral; d'autres études et observations sont actuellement encore en cours.

Nous ne voulons pas parler ici du plan prévu pour la recherche ni sur les méthodes qu'on a employées, ni sur les résultats obtenus localement mais on parlera seulement de l'équilibre eaux douces — eaux salées dans la zone soumise à la recherche : on considérera en outre les possibilités et les limites d'un prélèvement, pour l'irrigation, des eaux douces de cette nappe; on parlera donc, sur la base des données acquises par la recherche effectuée par l'Office d'Irrigation des Pouilles pendant les cinq dernières années, de l'aspect général du problème commun à l'utilisation des eaux souterraines dans les zones côtières.

Caracteristiques hydrologiques de la nappe consideree

La nappe en question imbibe les calcaires du Crétacé qui forment le fond du sol de la région des Pouilles : ce fond se présente formé par une pile de couches détachées

et fracturées, même dans le sens vertical, qui s'étend à plus de mille mètres au dessous du niveau de la mer. Ces formations du Crétacé affleurent sur une grande partie du territoire, alors qu'elles sont recouvertes, tout le long de la bande côtière ionienne et de l'Adriatique, par des formations d'arénaires, d'argiles et de sable, souvent assez épaisses.

C'est à la forte fracturation des formations affleurantes que l'on doit la pénurie des écoulements superficiels sur toute cette zone et, par contre, la riche circulation hydrique souterraine : les précipitations atmosphériques qui tombent sur les calcaires affleurant pénètrent ensuite, à travers les fissurations de la formation rocheuse, dans le sous-sol où elles forment un ample bassin souterrain.

En raison de la résistance qui s'oppose à l'écoulement des eaux vers la mer, la surface piézométrique de la nappe se trouve inclinée vers les point de débouchement avec une pente variable, en général, de 0,3 à 0,5 °/°°.

Selon ce que nous avons dit, étant donné que les calcaires s'étendent très au dessous du niveau de la mer, ceux-ci, en profondeur, sont envahis par les eaux de mer environnant la région; la masse d'eau douce, formant la nappe, se trouve alors, en raison de sa moindre salinité, flottant sur ces eaux plus salées situées au dessous (comme les icebergs), selon ce qui est indiqué schématiquement dans la fig. 2, où :

t = la hauteur du niveau de la nappe sur la mer;
h = la profondeur de l'eau douce au dessous du niveau de la mer;
D = le poids spécifique de l'eau de mer;
d = le poids spécifique de l'eau douce.

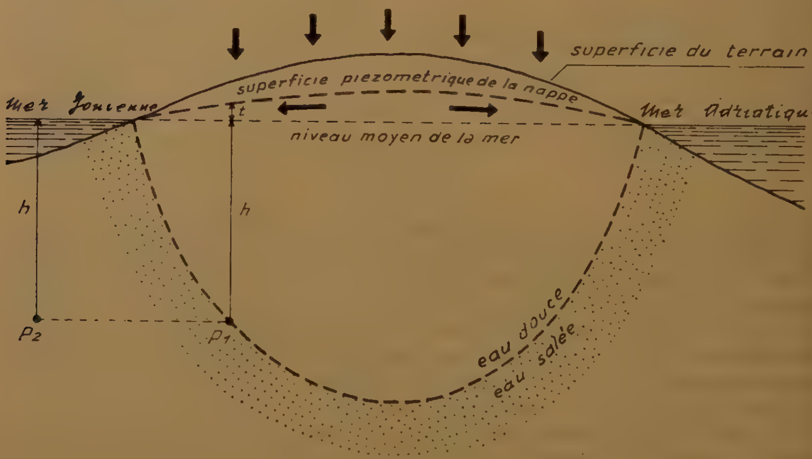


Fig. 2

La pression sur le point $P_2 = h \cdot D$, tandis que la pression sur le point $P_1 = (h + t) \cdot d$; si la pression en P_1 est égale à la pression P_2 on aura que : $h \cdot D = (h + t) \cdot d$, et par conséquent :

$$h = \frac{t \cdot d}{(D - d)} \quad \text{et} \quad \frac{h}{t} = \frac{d}{(D - d)}$$

ceci signifie que les profondeurs entre lesquelles on peut trouver les eaux douces h sont directement proportionnelles à la valeur de la hauteur des eaux douces sur la mer t (cote piézomètrique de la nappe).

Dans la région des Pouilles et en particulier sur la partie qui s'étend entre la mer Adriatique et l'Ionienne se trouvent deux directions principales de l'écoulement dirigées, grosso-modo, l'une vers l'Adriatique et l'autre vers la mer Ionienne, ce que montre schématiquement la fig. 2.

Les recherches effectuées ont montré que :

— le rapport $h = \dfrac{t \, . \, d}{(D - d)}$ résulte effectivement exact dans l'hydrologie souterraine des Pouilles, en conséquence de l'équilibre statique de deux liquides ayant une densité différente : ceci même si le phénomène hydrologique souterrain est effectivement dynamique étant caractérisé par l'afflux et le reflux des eaux douces;

— pour une valeur du poids spécifique de 1,028 pour l'eau de mer et 1,0028 pour l'eau douce, le rapport $h/t = 40$: par conséquent pour un mètre de hauteur de la nappe au dessus du niveau de la mer correspond une épaisseur d'eau douce, au-dessous du niveau de la mer, égale à 40 mètres (pour fixer les valeurs de ces poids spécifiques on a tenu compte que la densité des liquides dépend de la salinité et de la température; cette dernière, à son tour, dépend de la profondeur où se trouvent les liquides;

— jusqu'à 4/5 de la profondeur où se trouve le contact théorique eau douce-eau salée, la salinité totale varie de 0,6 à 5 gr/lt (les valeurs majeures se trouvent dans les parties plus basses); par contre sur le dernier cinquième de la profondeur totale le titre salin augmente brusquement à 20-30 gr/lt : ceci constitue une zone de salinification qui précède la limite des eaux de mer (selon ce qui résulte du diagramme de la fig. 3 effectué d'après les résultats de prélèvements d'échantillons d'eau à diverses profondeurs dans les puits de forage); par conséquent le rapport h/t se réduit pratiquement à 32 (c'est-à-dire à 4/5 de 40) : il en dérive donc que lorsque la pente piézométrique de la nappe oscille entre 0,3 et 0,5 $^0/_{00}$, soit en moyenne 0,4 $^0/_{00}$, à

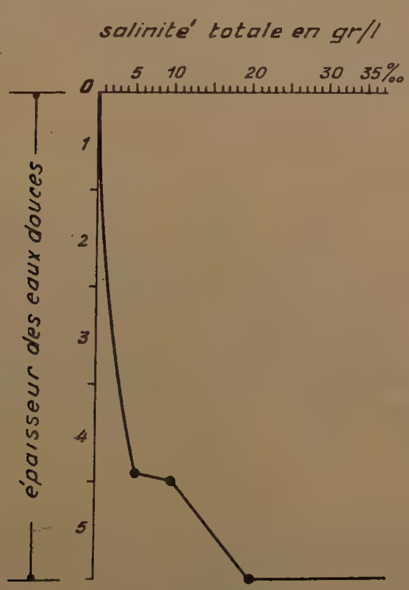


Fig. 3

1 km de la côte on peut trouver de l'eau douce (ayant une salinité totale comprise entre 0,6 et 5 gr/lt) jusqu'à la profondeur au-dessous du niveau de la mer de m 0,4 × 1 × 32 = m 12,8 alors qu'à 20 km de la côte on pourra trouver des eaux douces jusqu'à la profondeur de m 0,4 × 20 × 32 = m 256 au-dessous du niveau de la mer.

— la pente piézométrique s'annule le long de la ligne côtière lorsque les calcaires y affleurent; par contre, lorsque ceux-ci sont recouverts par des formations imperméables jusqu'au dessous du niveau de la mer, la nappe arrive à passer au-dessous au moyen d'un remous ou bien elle dévie pour trouver une issue en d'autres points de la côte.

Débit du prélèvement d'eau possible dans un puits

Selon ces caractéristiques de la nappe un prélèvement d'eau modifie l'équilibre du système hydrologique.

Tout particulièrement le puisage d'eau d'un puits, en produisant un abaissement du niveau statique de la nappe, détermine un surhaussement de la surface de contact eau douce-eau salée et, selon ce que nous avons déjà dit, on devrait avoir précisément un surhaussement des eaux salées égal à 32 fois la valeur de la dépression apportée au niveau de la nappe, par le fait de ce prélèvement.

Actuellement on ne dispose pas encore de données expérimentales qui permettent de connaître complètement les caractéristiques de cette action dynamique qui, en étant entre autre influencée aussi par le système de cassure de la roche, peut varier d'une zone à l'autre; surtout on ne connaît pas exactement l'« hystérésis » du phénomène, c'est-à-dire on ne connaît pas avec quel retard, par l'action qui abaisse le niveau, on a un surhaussement des eaux salées.

Aux effets de l'évaluation que l'on va faire on peut considérer que les formations où se trouvent ces nappes d'eau sont celles ayant une fissuration homogène.

Pour éviter, théoriquement, que les eaux salées atteignent le fond du puits il est nécessaire, selon ce que nous avons dit, que la dépression limite (Δh_1) se maintienne dans les limites suivantes :

$\Delta h_1 \,.\, 32 = 32 \,.\, t - \mathrm{L}$ d'où il s'ensuit que

$\Delta h_1 = \dfrac{32 \,.\, t - \mathrm{L}}{32}$ c'est-à-dire

$\Delta h_1 = t - \mathrm{L} \,.\, 0{,}03125$

où Δh_1 représente la « dépression limite » du niveau de la nappe pendant le prélèvement d'eau, t est la cote du niveau statique de la nappe au dessus de la mer et L la profondeur du puits sous le niveau de la mer (fig. 4).

Etant donné que l'eau saumâtre en forme de monticule ascendant qui se produit en conséquence du prélèvement, se rompt avant d'atteindre la position théorique d'équilibre en salant ainsi la nappe d'eau douce environnante, il devient nécessaire de maintenir la « dépression limite » entre des valeurs mineures, c'est-à-dire entre une « limite de sécurité » (Δh_S) qui pourrait être, par précaution, la moitié du Δh_1 déjà cité, c'est-à-dire :

(') $$\Delta h_s = \frac{t - \mathrm{L} \,.\, 0{,}03125}{2}$$

Le débit correspondant à cette « dépression de sécurité » est, en ligne de précaution, le « débit puisable » du puits.

Dans le diagramme de la fig. 5, tiré de la formule (') on peut lire les valeurs de la dépression de sécurité Δh_S correspondant à certaines valeurs de L et t.

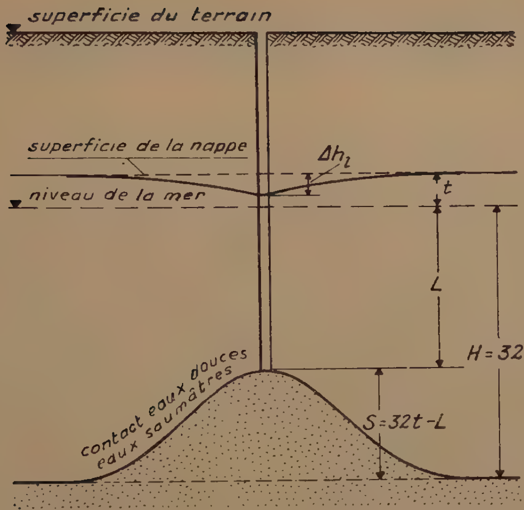


Fig. 4

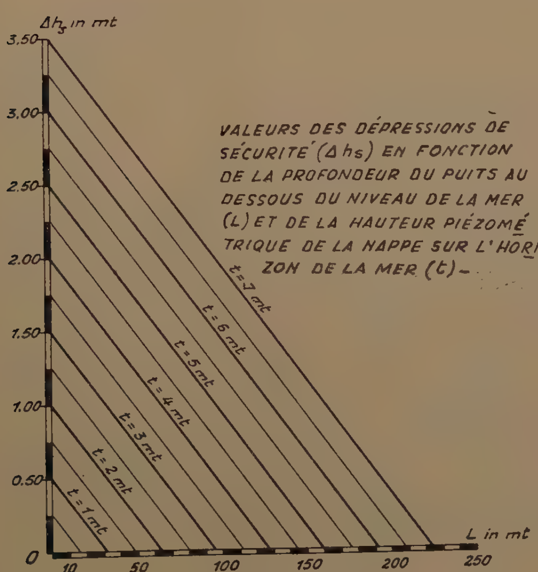


Fig. 5

Il peut arriver aussi que d'un puits qui permet un prélèvement d'eau même assez important, on puisse effectivement puiser un débit continu et modeste d'eau douce.

Etant donné que la valeur de la « dépression de sécurité » augmente au fur et à mesure que la profondeur du puits au dessous du niveau de la mer diminue, alors

que la puissance hydrologique du puits augmente, normalement, avec la profondeur (c'est-à-dire, en approfondissant le puits on peut en général puiser la même quantité d'eau en diminuant, cependant, le niveau) il existe un « optimum » pour la profondeur du puits auquel correspond le « meilleur rendement » du puits.

Evaluation de la disponibilite hydraulique

Il est relativement assez simple d'établir un bilan hydrologique des nappes aquifères qui imbibent une couche uniforme et s'appuient sur une formation imperméable : d'autre part ce n'est pas un problème difficile d'établir, grosso-modo, quel est le débit qu'on peut puiser de ces nappes même si celles-ci se trouvent en contact avec la mer; le souci de provoquer, à la suite d'un puisage, la salure des eaux douces de la nappe existe, effectivement, seulement dans les zones côtières et, de toute façon, pour ces territoires où le fond imperméable, lit de la nappe, se trouve au-dessous du niveau marin. Théoriquement, sur ces nappes on peut puiser, sur la partie où le lit de la nappe se trouve à une cote supérieure au niveau de la mer, tous les apports hydrauliques qui alimentent son bassin, sans pour cela causer des déséquilibres dangereux à la qualité de l'eau.

L'évaluation des puisages possibles par contre est assez problématique pour les nappes flottant au-dessus des eaux de mer, selon le type carstique des Pouilles, étant donné qu'il s'agit d'un système hydraulique instable assez plus complexe en raison de l'influence de divers facteurs.

L'accroissement et le décroissement continuel de la surface piézométrique de la nappe, en raison des afflux et des reflux saisonniers, détermine une variation cyclique annuelle des caractéristiques géométriques du système hydrologique.

Sur un ensemble aussi dynamique il est bien difficile d'établir l'action de puisages éventuels : même avec les éléments que l'on peut relever d'une recherche préliminaire, même assez soignée, il n'est pas possible de prévoir, avec exactitude, quel devra être le comportement de la nappe durant le pompage.

D'autre part, en voulant donner cours à une utilisation importante dans le but de l'irrigation, une évaluation, tant soit peu orientative, des ressources hydrauliques souterraines puisables pendant la saison des irrigations, devient nécessaire : ceci car on ne peut entreprendre la construction d'installations d'irrigation très coûteuses et de la lourde transformation agraire qui s'ensuit à moins d'avoir la certitude qu'on puisse disposer de l'eau nécessaire.

La complexité d'une telle évaluation et la nécessité de s'appuyer sur des hypothèses et sur de simples suppositions pour la réalisation pratique du problème peut résulter évidente par l'illustration des puisages possibles, pour l'irrigation, de la nappe carstique de la région des Pouilles.

On doit poser tout d'abord que l'ensemble hydrologique souterrain des Pouilles est fourni par divers « bassins » hydrologiques que l'on peut considérer comme indépendants, c'est-à-dire constitués, en raison de conditions géo-stratigraphiques spéciales, par des formations particulières et séparées, susceptibles d'un propreb ilan hydrologique.

Dans les Pouilles les précipitations atmosphériques sont concentrées pendant les mois d'automne et d'hiver, alors qu'on atteint 70 % de la valeur totale des précipitations annuelles. Lorsque, fin septembre, arrivent à la nappe les premières précipitations d'automne-hiver absorbées par les calcaires qui affleurent, son niveau commence une phase d'élévation due au fait que la nappe n'est pas en mesure d'écouler rapidement toute la quantité d'eau qu'elle reçoit; le niveau continue à monter pendant toute cette période, que l'on peut appeler « de régime influencé ». jusqu'au moment où l'affluence de l'eau est plus grande que les écoulements; lorsque l'apport des eaux de pluie est inférieur aux écoulements, le niveau de la nappe s'abaisse; quand l'apport

des pluies vient à manquer l'abaissement continue et la nappe laissera écouler l'eau qu'elle avait emmagasinée; cette phase, dite de « régime propre », commence en général vers les mois de février-mars et se termine fin septembre lorsque les nouveaux apports hydrauliques des pluies d'automne arrivent à la nappe : à ce moment commence alors un nouveau cycle.

Etant donné les caractéristiques de l'emmagasinement souterrain, ample et profond, vu la nature de la roche qui le contient, qui est stratifiée surtout dans le sens horizontal, on peut considérer que les surhaussements et les abaissements annuels du niveau de la nappe ne produisent pas des variations sensibles de la position du plan de séparation entre les eaux douces-eaux salées; seulement sur la côte, où les eaux douces ont une modeste épaisseur, cette variation pourra se faire sentir.

Selon ce qui est intuitif et selon ce qu'on a pu facilement remarquer par l'observation des sources, l'importance des écoulements dépend du niveau piézométrique de la nappe; ces écoulements diminuent au fur et à mesure que le niveau de la nappe s'abaisse et au-dessous d'une certaine cote piézométrique, les écoulements se réduisent au point de devenir négligeables par rapport au total des écoulements annuels. On peut donc considérer, dans le calcul orientatif des débits puisables, les écoulements que l'on a jusqu'au moment où la nappe atteint le niveau piézomètrique d'étiage, en négligeant les écoulements plus modestes de la nappe lorsque celle-ci s'abaisse au-dessous de cette cote.

Cette simplification hypothétique, qui toutefois trouve une ample justification dans les observations effectuées sur les écoulements de la nappe pendant les mois d'été et même dans la genèse de la présence des eaux douces au-dessous des eaux salées, permet d'admettre la possibilité d'effectuer des puisages d'une certaine importance sur la nappe pendant la saison des irrigations : par contre cette possibilité devrait être évitée si l'on admet que la nappe présente des écoulements copieux et non négligeables même avec des charges piézométriques assez basses.

En faisant des hypothèses sur ce que nous avons exposé on trouve que la quantité d'eau que l'on peut puiser est représentée par l'entité de l'alimentation hydraulique extérieure qui détermine le rechargement de la nappe : ceci subordonné aux effets que l'abaissement du niveau piézomètrique, dû au puisage, peut provoquer sur l'équilibre eaux douces-eaux salées.

Si l'on veut calculer le puisage possible dans un « bassin » bien determiné il faut remarquer et fixer les éléments caractéristiques suivants du « bassin » :

S^0 = Superficie totale du bassin, en km²;
S_a = Superficie d'absortion du bassin, en km²; constituée par les affleurements de calcaire fissuré ou par d'autres roches perméables;
S_{pl} — Etendue, en km², des zones où la nappe coule à l'air libre et où l'on peut, par conséquent, déterminer un surhaussement de la nappe;
P — Précipitations totales du semestre automne-hiver (octobre-mars) en mm;
a = Coefficient d'absorption des eaux de la part des formations perméables;
c — Coefficient de contenance des calcaires.

L'afflux des eaux dans la nappe pendant le semestre automne-hiver est en m³

$$P_a = S_a \cdot P \cdot a \cdot 1000$$

L'afflux P_a produit un surhaussement de la nappe, dans les zones où elle coule à l'air libre, en mètres :

$$s = \frac{P_a}{S_{pl} \cdot 1.000.000 \cdot c}$$

Etant donné que les pluies peuvent faire monter la nappe jusqu'à augmenter son niveau de s m, il s'ensuit la possibilité de puiser l'eau de celle-la jusqu'à abaisser s m son niveau au-dessous de celui d'étiage; dans ce cas en effet, les apports automne-hiver rétabliraient le niveau d'étiage et ainsi on n'aurait pas d'écoulements en mer

(les écoulements de la nappe ayant un niveau piézométrique inférieur à celui d'étiage sont considérés négligeables).

En réduisant, par précaution, la valeur de cet abaissement limite à la valeur s_1 on a que pour chaque mois des six mois de la saison de l'irrigation on peut abaisser le niveau de la nappe de m $s_2 = \frac{s_1}{6}$.

Par conséquent, pour chaque km² de la superficie du « bassin » là où la nappe coule à ciel ouvert, on pourra puiser par mois, en m³ :

$$Q_m = s_2 \cdot S_{pl} \cdot 1.000.000$$

ce qui correspond en litres/seconde :

$$Q_s = \frac{Q_m \cdot 1000}{30 \text{ jours} \times 24 \text{ heures} \times 3.600 \text{ secondes}}$$

(Q_s dans les Pouilles, par un calcul de ce genre, prend la valeur de 4 l/s environ).

Le surhaussement des eaux salées correspondant à l'abaissement s_1 qui se produit dans la nappe pendant les six mois de la saison de l'irrigation et qui devrait être de 32 m $\times$ s_1, selon ce que nous avons cité, ne peut causer de trop graves préoccupations dans les Pouilles, car, par les conditions géo-stratigraphiques spéciales existantes, on a un certaine « hysterésis » du mouvement des eaux salées ; par conséquent le mouvement ascensionnel des eaux du fond, qui devrait commencer les derniers mois de la saison de l'irrigation, reste bloqué par l'apport des précipitations d'automne et s'annule au début de la saison d'irrigation successive.

Le phénomène du surhaussement des eaux salées du fond, selon ce que nous avons dit, peut donner des préoccupations sur les zones côtières où l'épaisseur des eaux douces est modeste; étant donné que pour les conditions géo-hydrologiques des Pouilles, une masse d'eau douce de 20-35 m d'épaisseur est nécessaire afin de créer un obstacle efficace à l'invasion des eaux de mer, il semble opportun de ne pas effectuer des puisages d'eau sur une « zone côtière de sécurité » de 3 km de profondeur (en considérant la valeur moyenne du niveau piézométrique de la nappe égal à 0,4 ‰); cette zone de sécurité évidemment n'est pas nécessaire là où les côtes sont bordées jusqu'à quelques dizaines de mètres au-dessous du niveau de la mer, par des couches de sol imperméables, car ces conditions de la stratification garantissent un obstacle à l'invasion de la mer.

De ce mémoire schématique il résulte que le puisage d'eau possible pendant la saison de l'irrigation, qui correspond à la période d'étiage de la nappe, dépend de la possibilité de faire fonctionner le bassin hydrique souterrain comme un réservoir d'emmagasinement; les limites de ces possibilités dépendent des conditions géo-hydrologiques (coefficients d'absorbtion — de perméabilité — de contenance, etc.).

D'autre part vu qu'il est évident que l'on ne peut pas prévoir, avec la certitude qui serait nécessaire les limites de cette possibilité, l'utilisation de nappes d'eau douces soutenues par des eaux saumâtres, en plus d'une recherche préliminaire très attentive, capable de fournir les éléments nécessaires pour le calcul d'orientation qu'on a cité, demande aussi une augmentation graduelle des utilisations basée sur des observations attentives effectuées au cours de puisages contemporains et prolongés; ce n'est que par un programme d'augmentation progressive des puisages qu'on pourra arriver à l'utilisation rationnelle et intégrale des ressources hydrauliques disponibles; par contre une utilisation imprudente et indisciplinée peut causer une salure de l'eau douce qui même sans remède porterait préjudice à la possibilité d'une utilisation. Par conséquent il sera nécessaire que pour l'utilisation des nappes de ce genre on procède avec la plus grande attention en se basant sur un « plan d'utilisation » en prédisposant les contrôles nécessaires et en effectuant aussi des observations et des relèvements continuels et attentifs.

WITHDRAWING FRESH WATER AND SALT WATER SEPARATELY FROM WELLS TURNED SALINE BY UPCONING OF BRACKISH GROUNDWATER

Communication by the Netherlands Government Institute
for Water Supply, The Hague

The wells to be described are situated in a heavily pumped coastal dune area, at a distance of 4 km from the sea shore.

They withdraw their water from a confined aquifer, consisting of pleistocene sands of marine and continental origin, and covered by alluvial layers of low permeability. The screens of the wells are placed between 25 m and 40 m below sea level.

The pleistocene aquifer has a transmissivity of about 700 m^3/day. The drawdown in the wells is 0.85 m for a withdrawal of 20 m^3/h (the average capacity of wells in this aquifer). Due to heavy pumping in the area, the static water level in the wells is about 7 m below sea level, which is some 10 m below the original natural groundwater potential. Many wells in the area show a considerable rise in salinity of the groundwater pumped; several of them had to be abandoned.

In 1955, on the advice of the Government Institute for Water Supply, the owner of one of the well fields, the paper mill of Van Gelder Zonen, started experiments, in order to investigate whether it would be possible to put these abandoned wells into operation again by withdrawing fresh water from the top of the wells and salt water from the bottom by means of separate pumps. The location of the wells at a short distance from a brackish water canal, into which the salt water pumped from the wells could be discharged, facilitated the experiments.

The construction of the well selected for the experiment is shown in fig. 1. Fig. 2 shows the rise in salinity of the water when this well was put into operation in the normal way, i.e. with one pump placed above the well screen. The salinity rose from about 600 p.p.m. to 900 p.p.m. within 18 days, although the quantity pumped amounted to only 10 m^3/h. Fig. 3 shows the results of the first experiment, when fresh water was withdrawn from the top of the well and salt water from the bottom. These results looked sufficiently favourable to continue the experiment on a larger scale.

Since, however, special pumps had to be ordered for this purpose, it was only in November 1956 that the experiment could be continued. This time two wells were put into operation. In the period of November 1956 - June 1957 the discharge of the upper pump of the first well was gradually increased from 10 m^3/h to 15 m^3/h; the discharge of the lower pump was maintained at 5 m^3/h. The chlorine content of the water discharged by the upper pump did not change much in this period: it stayed between 70 and 100 p.p.m. Cl', with an average of 85 p.p.m. The salinity of the water discharged by the lower pump increased from about 700 to 1500 p.p.m.

The discharge of the upper pump in the second well was increased from 7 to 10 m^3/h; the discharge of the lower pump was kept at 3 m^3/h. In the period November 1956 - June 1957 the salinity of the fresh water rose from 150 to 240 p.p.m.; the salinity of the brackish water discharged by the lower pump rose from about 900 to 1400 p.p.m.

The experiments are being continued. The results obtained up till now, however, show already that it is possible both from a technical and an economical point of

FIG. 1

CONSTRUCTION OF WELLS

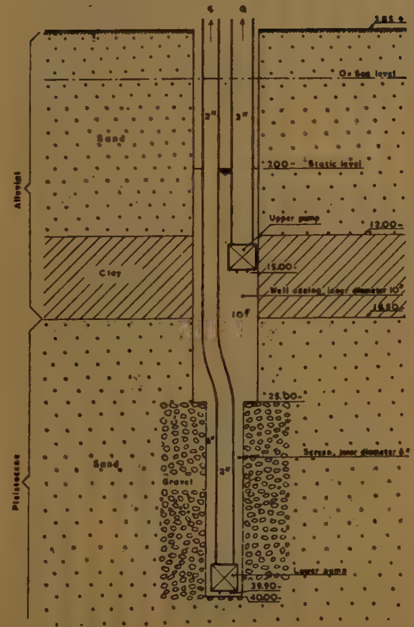


FIG. 2

RISE IN SALINITY IN CASE OF NORMAL OPERATION OF TESTWELL 13A

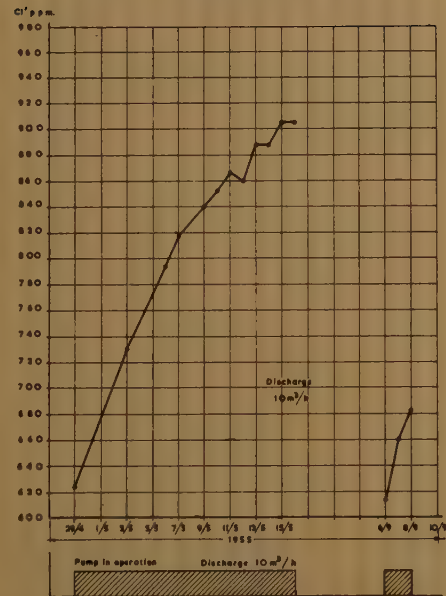
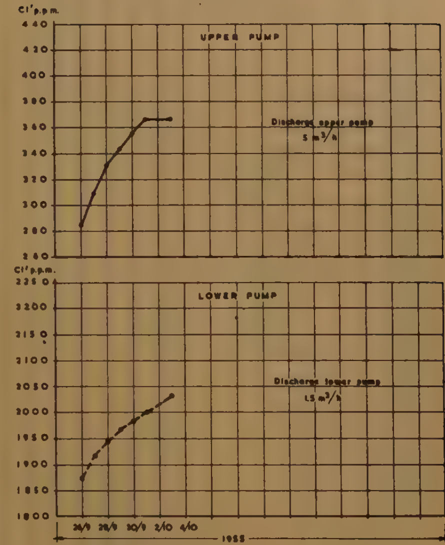


FIG. 3

SALINITY OF WATER PUMPED SEPARATELY FROM TOP AND FROM BOTTOM OF TESTWELL 13A



view, to withdraw fresh water from wells which turned saline by upconing of brackish groundwater, by inserting a second pump which withdraws the brackish water entering the well through the lower part of the screen. A condition to be complied with is, that it should be easy to dispose of the brackish water discharged by this second pump.

SYMPOSIUM SUR L'INFLUENCE DE LA VÉGÉTATION SUR LE CYCLE HYDROLOGIQUE

La séance est ouverte à 14 ½ sous la présidence de Mr. Earl Harbeck jr.

Présents : G. TISON, Belgium; M. A. KOHLER, U. S. A.; E. L. HAMILTON, U. S. A.; W. E. HIATT, U. S. A.; H. A. WILM, U. S. A.; W. ALLARD, U. K.; HARRY F. BLANEY, U. S. A.; THOMAR W. ROBINSON, U. S. A.; S. BUCHAN, U. K.; A. VOLKER, Holland; J. Th. THIJSSE, Holland; G. E. HARBECK jr. U. S. A.; W. M. BERRY, Canada; M. B. BUHLE, U. S. A.; George B. MAXEY, U. S. A.; L. SERRA, France; D , Canada; J. P. BRUCE, Canada; Geo. W. ROBERTSON, Canada; E. R. LEMON, U. S. A.; K. M. KING, Canada; D. F. WITHERSPOON, Canada; D. E. ELRICK, Canada; F. K. NÖRING, Germany; W. FRIEDRICH, Germany; H. FLOHN, Germany; G. REMENIERAS, (France); Y. A. MAGEED (Sudan); BEN OSMAN ESSAAD (Tunisie); R. KELLER, Germany; H. I. SELKRIGG, U. S. A.; A. A. CRAPS, Canada; R. K. LINSLEY, U. S. A.; C. L. WALKE, U. S. A.; Robert SCHNEIDER, U. S. A.; R. E. BERGSTROM, U. S. A.; G. P. WILLIAMS, Canada; Gordon MANLEY, U. K. (GB); F. FOURNIER, (France); W. F. J. M. KRUL (Netherlands); W. VAN DER BIJL, U. S. A.; John F. MANN, Jr., U. S. A.; Leonard SCHIFF, U. S. A.; Donald W. BOYD, Canada; P. D. BAIRD, U. K.; H. R. THOMPSON, Canada; Roger F. TOMLINSON, U. K.; G. W. ROWLEY, Canada; Max SUTER, U. S. A.; VIBERT A. M., France; SCHOELLER, H , France; A. F. GEIGER, U. S. A.; D. D. SMITH, U. S. A.; Ira HUNT, U. S. A.; P. O. WOLF, U. K.; G. NYBRANT, Sweden; Herbert SCHITZKE, U. S. A.; J. KOLUPAILA, U. S. A.; M. S. SACHS, U. S. A.; Ralph N. WILSON, U. S. A.; Harry E. SCHWARZ, U. S. A.; J. TIXERONT, Tunisie; B. GUILMET, France; M. PARDÉ, France; J. K. LATTO, Canada; W. STICHLING, Canada; F. I. MORTON, Canada; H. KURON, Deutschland; GRAHMANN, Deutschland; A. G. SCUKA, Canada; D. M. BROWN, Canada; L. J. CHAPMAN, Canada; W. H. DURUM, U. S. A.; S. BUCHAN, U. K.; L. J. TISON, AIHS.

M. Robinson présente sa communication.

Elle donne lieu à une intervention de Mr. Harry F. Blaney :

With the water table at same depth will the rate consumptive use of water vary for salt cedar and cottonwoods ?

Answer: Use of water rates in Western U. S. varies with different types of vegetation.

La communication de MM. Baden et Eggelmann amène la remarque suivante de M. Remenieras : Il a été signalé que l'exploitation totale (c.-à-d. la suppression) de certaines tourbières belges a conduit à une diminution des crues d'hiver sur le cours d'eau émissaire. Cela peut s'expliquer en assimilant la tourbière en hiver à une éponge complètement gorgée d'eau *dont le pouvoir de rétention est quasi nul* et en tous cas inférieur à celui des terrains cultivés qui l'ont remplacée. La vitesse de propagation des eaux est peut être aussi plus grande dans les tourbières que dans le sol sous-jacent.

La communication de M. Ostromeck et celle de M. Bae ne donnent lieu à aucune intervention.

Mr. P. Wolf présente la communication de M. Law. Elle donne lieu à des interventions de Mr. Wilm et de Mr. Thijsse : M. Wolf donne les renseignements demandés en faisant remarquer que ces indications se trouvent dans l'étude de M. Law qu'il a dû résumer.

Mr. Harry E. Schwarz : Have records been kept of wind velocity, direction and steadiness during the rainfalls for which interception was measured? The application of a Lysimeter result on a large wooded area would be greatly influenced by the exposure to wind causing the canopy to slake and shed the water it intercepts.

Answer: There is a standard meteorological station near the lysimeter and wind speeds and directions are recorded there.

The Lysimeter is in the centre of a wooded area and the conditions at the edges of the Lysimeter may be regarded as uniform.

Mr. Volker refers to a similar experience in the Netherlands. With lysimeters in a dune catchment area, it has been found that the infiltration in areas with forests was much less than in bare lands.

The Dutch lysimeter commission will be glad to put the figures at the disposal of Mr. Law.

Prof. Krul answering Mr. Wolf request for results of similar experiments in other places,wants to point out that in the Netherlands and in Germany lysimeter experiments are being carried out on a fairly large scale. Some papers on lysimeters have been presented at former Congresses. It would be desirable to consider during our meeting in Toronto, whether it would be appropriate to have a standing Committee or to organize a symposium on lysimeter investigations under the guidance of our Association.

Cette idée sera reprise à l'Assemblée Générale et conduira à l'organisation d'un Symposium comme sujets, d'une part l'Eau et les Régions boisées et d'autre part, les lysimètres.

Mr. H. Blaney : What happens to deep percolation of water below root zone to ground-water ?

Is it available for pumping?

Answer: Subsoil is clay and no water is available for use from groundwater by pumping. Prof. J. Th. Thijsse observes that the smallness of the woodland area surrounding the lysimeter makes conditions exceedingly complex.

In his experience, Mr. Law's was the first experiment where the effect of the proximity of the edge of the woodland area on conditions at the lysimeter might be of major significance.

La contribution de Mr. K. Szesztay n'est présentée que par titre.

L'étude de M. Hallaire ne donne lieu à aucune intervention.

Celle de M. H. F. Blaney amène une intervention de Mr. Sachs:

In estimating annual consumptive use for planning purposes how are the climatic years selected: low years, high or median?

Answer: The selection is made by analysis of monthly and annual publications of climatic observations of the U. S. Weather Bureau and unpublished records. Rainfall records are used to obtain the critical low (dry) years and the high (wet) years for water supply. Mean monthly temperatures for these years are used to compute consumptive use by formula $u = k.f.$

Mr. W. van der Bijl:

1) How have the data in table 3 been obtained?

2) Are the data of Tables 2, 3 and 4 based on the observations of one or of more years?

Answer:

1) By soil-moisture depletion method, that is taking soil samples in 1-foot sections, within root zone before and after irrigation. Samples are weighted wet and dried at 110° C for 24 hours.

Mr. W. M. Berry asks:

What are the problems associated with mapping regional estimates of consumptive use, having regard to varying climatic, topographical and other influences?

Answer:

The primary problem is the availability of records of rainfall, temperature, wind velocity and irrigation records. If these data are available, then consumptive use can be computed.

Intervention of Mr. G. Maxey:

1) Do you use soil blocks in the soil-moisture depletion method?

Answer: No — we take soil samples and measure the moisture-content in the laboratory.

2) Would you cave to comment on the nature of movement of water in unsaturated soils? Answer: Not much is known about this phenomenon. Suggest asking L. A. Richards U. S. Salinity Lab., Riverside, Calif.

Mr. Y. A. Mageed: The difficulty with irrigation is the determination of the right times to apply the irrigation water. Is there any easy method to enable the farmer who cannot make soil sampling, etc., to determine the right time to apply his water.

Answer:

In California commercial soil laboratories take soil samples in Citrus orchards for moisture determinations and advise the farmers when to irrigate. Some farmers use augurs to exam the soil and can estimate amount of moisture available. Farmers can determine when to irrigate cotton, citrus and alfalfa by color of leaves.

Les discussions qui précédent ont montré tout l'intérêt pris par les participants à ce colloque et montrent l'importance qu'il faut attacher au prochain symposium sur l'Eau et les régions boisées d'une part et les Lysimètres d'autre part.

GRAPHS FOR ESTIMATING EVAPORATION FROM LARGE AREAS

K. SZESZTAY
Cand. of Eng. Sc.
Research Institute for Water Resources, Budapest
Hungary

SUMMARY

In the summer evaporation-season (i.e. in moderate zone from 1 March to 31 October) evapotranspiration is controlled by factors (1) of the evaporating capacity and (2) of the amount of water resources susceptible to evapotranspiration. Evaporating capacity of drainage areas is determined on the basis of monthly mean vapour pressure saturation-deficit and/or of the mean monthly temperature by graphs constructed from lysimeter data. The amount of water resources susceptible to evapotranspiration («evaporation opportunity») is characterized by indexes computed from precipitation data of the investigated month as well as the two previous months, and from the «winter precipitation index».

Graphs for estimating monthly and yearly evapotranspiration of natural drainage areas are constructed on basis of physical considerations and lysimeter data. After having determined monthly evapotranspiration data of a 20-30 years period for several catchment areas in Hungary, synthetic graphs were elaborated, from which means and extremes of monthly and yearly evapotranspiration can be easily read.

At the present state of our knowledge in hydrology the long period average of annual evaporation from closed catchment areas is the only characteristic of evapotranspiration that can be determined with any degree of accuracy. This value $\bar{E}$ may be expressed as the difference of the long-period mean annual precipitation $\bar{P}$, and of the long-period mean annual runoff R:

$$\bar{E} = \bar{P} - \bar{R} \qquad (1)$$

The volume of water evaporating from river basins in the course of a year, a month or any shorter period is unknown because in this phase of the hydrologic cycle the path of water particles is concealed from the human eye and cannot be traced even by means of the instruments used in modern observation techniques.

Measurements of evaporation carried out using *small samples* (pans or tanks filled with water or soil) constitute the basis of present investigations. The value of such measurements for determining actual evaporation from natural basins seems however to be questionable and is likely to remain so owing to the uncertainty introduced by various «scale effects» encountered in the interpretation of results thus obtained.

The measurement of natural evaporation meeting both technical and economical requirements by creating a widespread observation network is the primary task of applied hydrology in the new stage of its development.

Until sufficiently detailed data on natural evaporation over a long period will have been accumulated we shall be compelled to have recourse to indirect methods i.e., to considerations relying on the laws of physics and on data obtained by samples.

1. SUMMER AND WINTER EVAPORATION

The difference between summer and winter evaporation under moderate climates lies in the physical fact that in winter the amount of water available for evaporation

is always in excess of the evaporative power, whereas during the summer period, owing to the scarcity of available water significant differences can be observed between actual evaporation and the evaporative power. As revealed by lysimeter observation data ([1]) and soil — humidity records ([6]) published in the literature, the winter period is restricted according to the above interpretation, to no more than the four-month period from November to February, the lack of water in March and October being already considerable even for practical purposes.

Since the volume evaporating in the four-month winter period defined above represents at the most from 6 to 8 per cent of the annual total,any further discrimination as to seasonal distribution would lead to no practical advantages. As preferable time-units for investigation, *individual months* or the *entire hydrological year* may be suggested.

2. Aids for the estimation of monthly evaporation

Evaporation in the *winter period* depends for all practical purposes on the evaporative power alone (the mean monthly vapor pressure saturation deficiency and/or the mean monthly temperature), the necessary amount of water being always available.

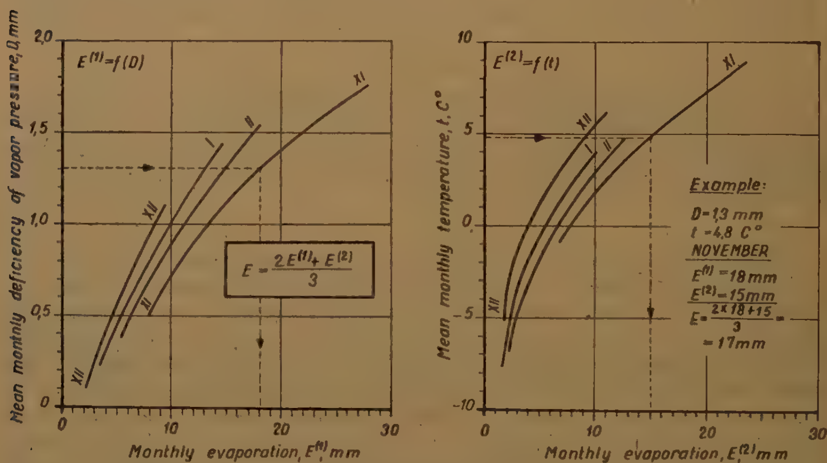


Fig. 1 — Graphs for estimation monthly evaporation in the winter season.

Aids presented in *Fig. 1.* have been compiled by evaluating monthly records of lysimeters installed in Germany.

The construction of aids *covering the months between March and October* constitutes a more intricate problem. Evaporation in these months is markedly affected by the amount of water available.

Water available for evaporation (evaporation opportunity) may be expressed by the index

$$M = M_1 + M_2$$

where M_1 and M_2 denote the moisture stored in the surface layers and in the deeper layers of the soil respectively. Values M_1 have been determined on the basis of

observation records compiled by the lysimeter station Eberswalde (Germany) for the years 1930 to 1937. The evaluation of numerical data characterizing the closeness of the graphically established relationships

$$E_i = f(D_i, P_i) \tag{2/a}$$

$$E_i = f(D_i, P_{i-1}) \tag{2/b}$$

$$E_i = f(D_i, P_{i-2}) \tag{2/c}$$

resulted in the formula

$$M_i = 2/3\, P_i + P_{i-1} + 1/3\, P_{i-2} \tag{3}$$

where P_i, P_{i-1} and P_{i-2} are monthly precipitation data for the month under consideration and the two preceding ones respectively weighted as indicated, while E is the monthly evaporation and D the mean monthly vapor pressure saturation deficiency (4).

Values M_2 have been obtained as related to the index of winter storage:

$$W = 4/3\, P_X + 2\, P_{XI} + 2\, P_{XII} + 5/3\, P_I + 2/3\, P_{II} \tag{4}$$

by the proportions:

$$M_2^{III} = 0{,}2\, W \tag{5/a}$$

$$M_2^{IV} = 0{,}3\, W \tag{5/b}$$

$$M_2^{V} = 0{,}4\, W \tag{5/c}$$

$$M_2^{VI} = 0{,}1\, W \tag{5/d}$$

(Roman numerals refer to individual months.)

Values of coefficients in Eqs. (5) have been selected so as to ensure for long period averages fair agreement between monthly evaporation data obtained by lysimeters and *monthly evaporation coefficients* expressed as

$$e_i = D_i M_i \tag{6}$$

for the summer period from March to October [4 and 7].

As regards transpiration from the vegetal cover, the *direct* regulating effect of temperature is independent from the saturation deficiency since plant life and the rate of growth are materially affected by the temperature t. Evapotranspiration in the summer months may therefore be described by the relationship

$$E = f(D, M, t) \tag{7}$$

containing four variables.

For purposes of quantitative investigation values E and M have been expressed —in agreement with principles adopted for comparative investigations—in the percentage of *long-period averages*, while values D and t represent deviations from the established mean. In other words, the relationship expressed by Eq. (7) has been investigated in the form:

$$E\% = f(\Delta D, M\%, \Delta t). \tag{7/a}$$

Considering the close relationship between ΔD and Δt and drawing on experience gained from the use of methods applied to similar problems previously (5), the relation (7) has been resolved into *two expressions*

$$E^{(1)}\% = f(\Delta D, M\%) \tag{8/a}$$

$$E^{(2)}\% = f(\Delta t, M\%) \tag{8/b}$$

each containing *three variables.* This simplification may entail practical advantages as well, since in case of certain data missing, the graphs constructed according to Eqs, (8/*a*) and (8/*b*) may still be used separately.

The following example will show how to determine the relations expressed by Eqs. (8/*a*) and (8/*b*). Data obtained for July are used, and reference is made to *Fig. 2.*

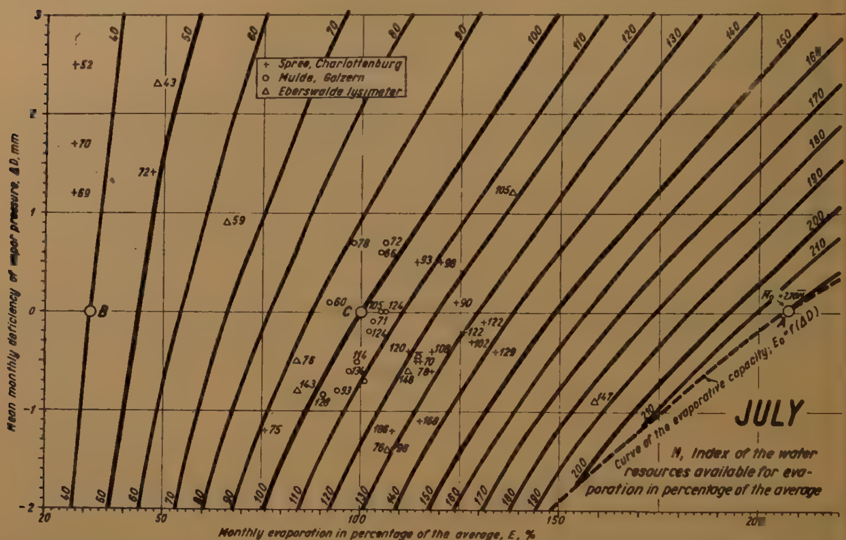


Fig. 2 — Example for elaborating monthly evaporation graphs in the summer season.

The first step was to plot points corresponding to data obtained for Germany and available from a publication of H. Kalweit [1]. The distribution of points thus obtained gives indications as to the order of magnitude only, the construction itself is guided essentially by different considerations.

The first problem to be solved in order to obtain fundamental information for the construction is to find out the average evaporation value for July, for the case when the available water is always sufficient to match the evaporative power. From the diagram in *Fig. 3.* constructed on the basis of German lysimeter observations an informative answer to this problem may be obtained. The diagram provided a means for computing for each month the approximate value of the evaporative power E_0 from the monthly average saturation deficiency D and/or the monthly mean air temperature *t*. Thereupon, by methods to be discussed later, the long-period averages of monthly evaporation E are determined. For the area cited as an example in *Fig. 4.* the average evaporative power in July i.e., 196 mm corresponds to 228 per cent of the actual evaporation of 86 mm. Evaluating in a similar manner average conditions for several areas it can be concluded, that an *average July evaporation*—under the moderate climates in consideration—*corresponding to the evaporative power will amount to from 200 to 220 per cent of the actual evaporation average.*

A similar assessment of data obtained for the remaining months, with due regard to the continuous variation in evaporation conditions in subsequent months has yielded the ratios E_0/E given in the upper part of *Fig. 5.* The discrepancy between actual evaporation and evaporative power is shown to attain maximum in July.

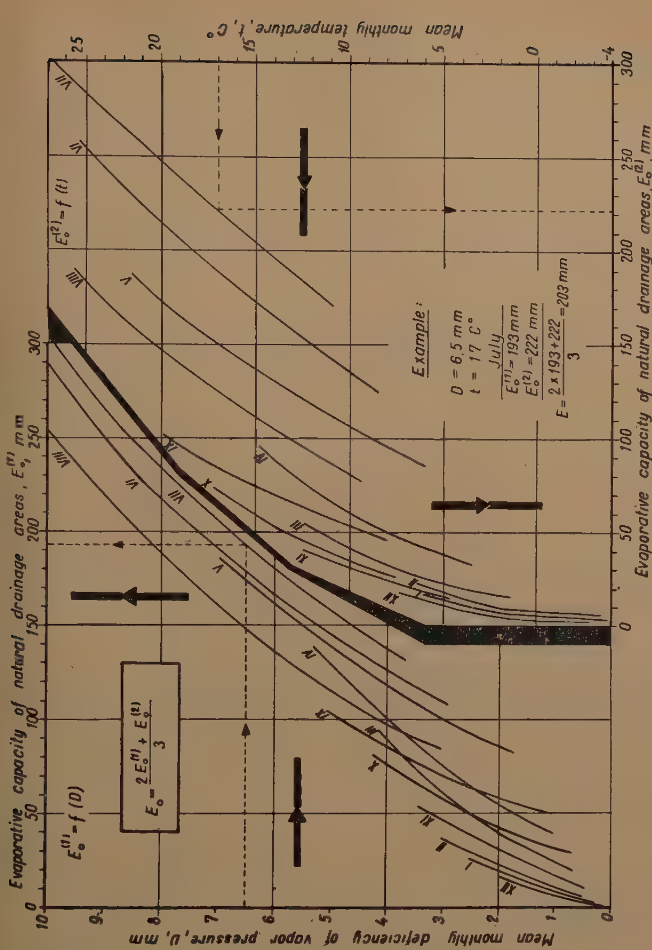


Fig. 3 — Graphs for estimation evaporative capacity of natural drainage areas.

The curve indicating the above ratio descends in both directions and attains unity in February and October.

Data obtained from the curve E_0/E furnished the first basic value for the construction of the monthly evaporation graphs (point A in *Fig. 2.*). Starting from point A representing long-period average conditions ($\Delta D = 0$) the curve expressing the relation

$$E_0\% = f(\Delta D)$$

(the dashed line over point A in *Fig. 2*) may be drawn for each month as indicated by the corresponding curve in *Fig. 3.*

The next problem is to find the precipitation value, i.e., index M_0, at which an evaporation E_0 could actually occur. As revealed by data compiled in *Fig. 4*, the annual average evaporative power E_0 over the catchment area of the Zagyva River

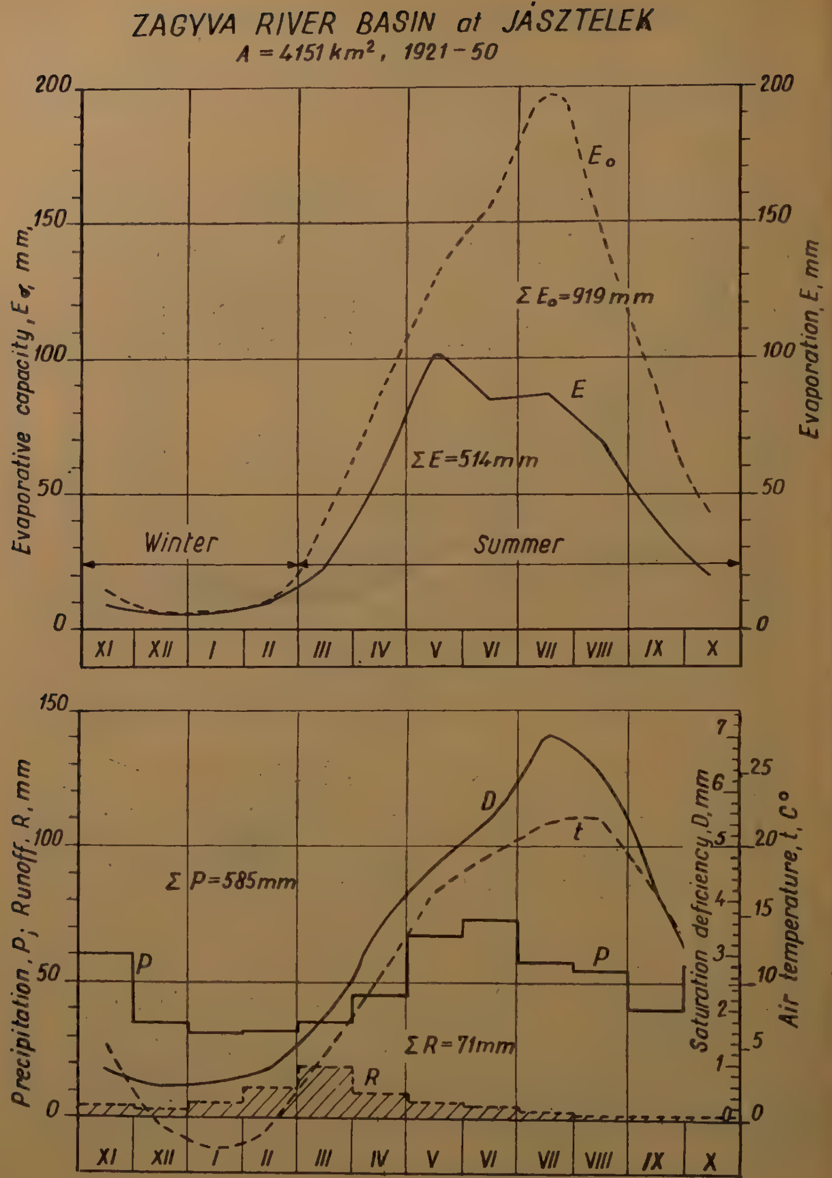


Fig. 4 — Comparison of the actual evaporation with evaporative capacity shows the effect of the lack in water resources available for evaporation.

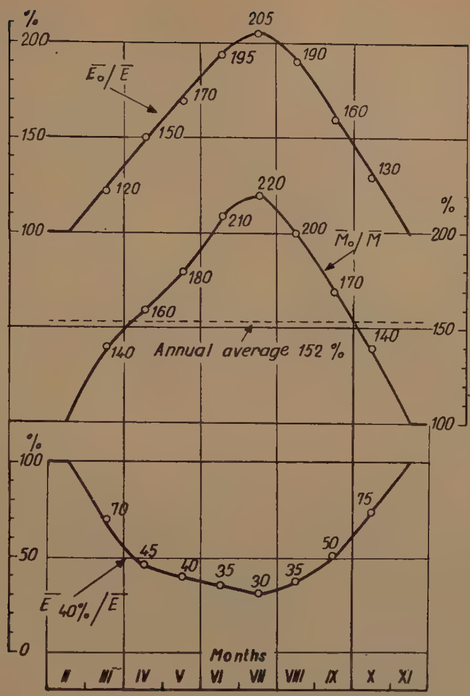


Fig. 5 — Physical considerations giving the basis of the construction of monthly evaporation graphs in the summer months.

at Jasztelek, is 919 mm. This requirement could be fulfilled by an annual precipitation

$$P_0 = E_0 + R_0 = E_0 + \alpha P_0 = E_0 : (1 - \alpha) = 919 : (1 - 0{,}13) = 1056 \text{ mm} \quad (10)$$

if the annual average runoff coefficient α is assumed to be constant. This theoretical value amounts to 181 per cent of the actual precipitation of 585 mm.

Monthly variations in $(P_0 - P)$ should follow those in $(E_0 - E)$, or, in other words, the actual precipitation could remain unchanged in the winter months and, starting from March the ratio M_0/M should increase gradually to its maximum in July, and then decrease gradually to attain unity in November.

The construction of the curve M^0/M in *Fig. 5.* was governed by similar considerations. It attains maximum at 220 per cent in July and, decreasing in both directions according to the ratio E_0/E, joins the horizontal corresponding to 100 per cent in February and November respectively. Numerical values for individual months have been selected and rounded off for practical purposes with a view to establishing agreement between the annual average of the ratio M_0/M and the average of values determined according to the above considerations for several catchment areas. (In determining the annual average, the months December and January have naturally also been allowed for by setting M_0/M at 100 per cent.) The value of round 150 per cent assumed as representative for the annual average has been adopted to include—with an accuracy inherent in such estimates— the probable increase in the runoff coefficient.

Thus for the construction of the graph in *Fig. 2* the following data have been determined: point A, the value $M_0 = 2{,}20$ M pertaining to point A, and the curve $E_0 = f(\Delta D)$ representing limit values at the right side of the range.

The left boundary of the range is to be established next.

Computing the water resources available for evaporation over a long period within a number of catchment areas in Hungary and in Germany it could be established that the value $M = M_1 + M_2$ falls—under moderate climates—in no month below 40 per cent of the long-period average. (The value of M represents—as has been shown—precipitation conditions of three successive months; the effect of extremely dry months is compensated to a certain extent by the precipitation in the preceding or subsequent ones and from the ground water.) Let us now determine the evaporation corresponding to average evaporative power ($\Delta D = 0$) if the amount of water available for evaporation is only 40 per cents of the long-period average.

The long-period July average of the index characterizing the volume of water available for evaporation in the catchment area of the Zagyva River at Jasztelek is according to Eq. (3)

$$M_{VII} = 2/3\, P_{VII} + P_{VI} + 1/3\, P_V = 38 + 75 + 23 = 134 \text{ mm.}$$

(Precipitation data were obtained by evaluating the record covering the period from 1921 to 1950.) Since the index features each precipitation with double value (the sum of weighting coefficients being: $2/3 + 1 + 1/3 = 2$) the 134 mm average corresponds to an actual precipitation of 67 mm, whose 40 per cent is 26 mm. Since under extremely dry conditions (when $M = 40\%$) surface runoff and deep percolation (storage) arising from precipitation are practically zero, the water volume computed to be 26 mm will entirely be evaporated. Thus over the area in consideration an evaporation of 26 mm in July equals the 40 per cent index, and corresponds to round 30 per cent of the long-period average of 86 mm.

Evaporation $E_{40\%}$ pertaining to $M_{40\%}$ was determined on basis of similar considerations for the other months and for several areas. The distribution over the year of the ratio $\bar{E}_{40\%}/\bar{E}$ is characterized by the lower curve in *Fig. 5.* which attains extreme values also in July. The transition in the spring and autumn months is here more abrupt than in case of the upper limit values, i.e., in extremely dry years the lack in water resources available for evaporation may be considerable as early as April and May resp. as late as September.

The curve representing the ratio $\bar{E}_{40\%}/\bar{E}$ contributed point B (*Fig. 2.*), i.e. the position of the $M = 40\%$ isometric curve. The inclination of the curve may be determined by the consideration that in extremely dry periods the resource of water available for evaporation is almost completely exhausted. Therefore evaporation can hardly be increased by increasing the evaporative power (the vapor pressure saturation deficiency), that is, the isometric line passing through point B is necessarily steep, almost vertical. The 40 per cent isometric curve will be steepest in June, July and August, whereas the effect of changes in the saturation deficiency—owing to the higher evaporation opportunity—will be felt to an increasing degree in months closer to the winter period.

Points A and B representing limit values of the range pertaining to the case $\Delta D = 0$, the value M_0 pertaining to point A and the curve expressing the relation $E_0 = f(\Delta D)$ as well as the isometric line of $M = 40$ per cent passing through point B have thus been determined for every single month by means of *Fig. 5.* Intermediate lines may be constructed on the basis of the following considerations: 1) the isometric $M = 100$ should pass through point C defined by values $\Delta D = 0$ and $P = 100\%$, 2) progressing from left to right the spacing of lines will become gradually tighter and 3) will deflect towards the E axis. Conditions (2) and (3) show that in extremely

dry periods evaporation is governed mainly by changes in the water volume available for evaporation and with increasing water content in the soil the role of the saturation deficiency will become more and more predominant and at the same time variations in available water volume will loose in significance.

The method outlined in detail in connection with *Fig. 2.* has been applied to the graphical solution of relations (8/*a*) and (8/*b*) for other summer months as well. The resulting diagrams can be seen in *Figs. 6 and 7*. Co-ordinates of a few characteristic

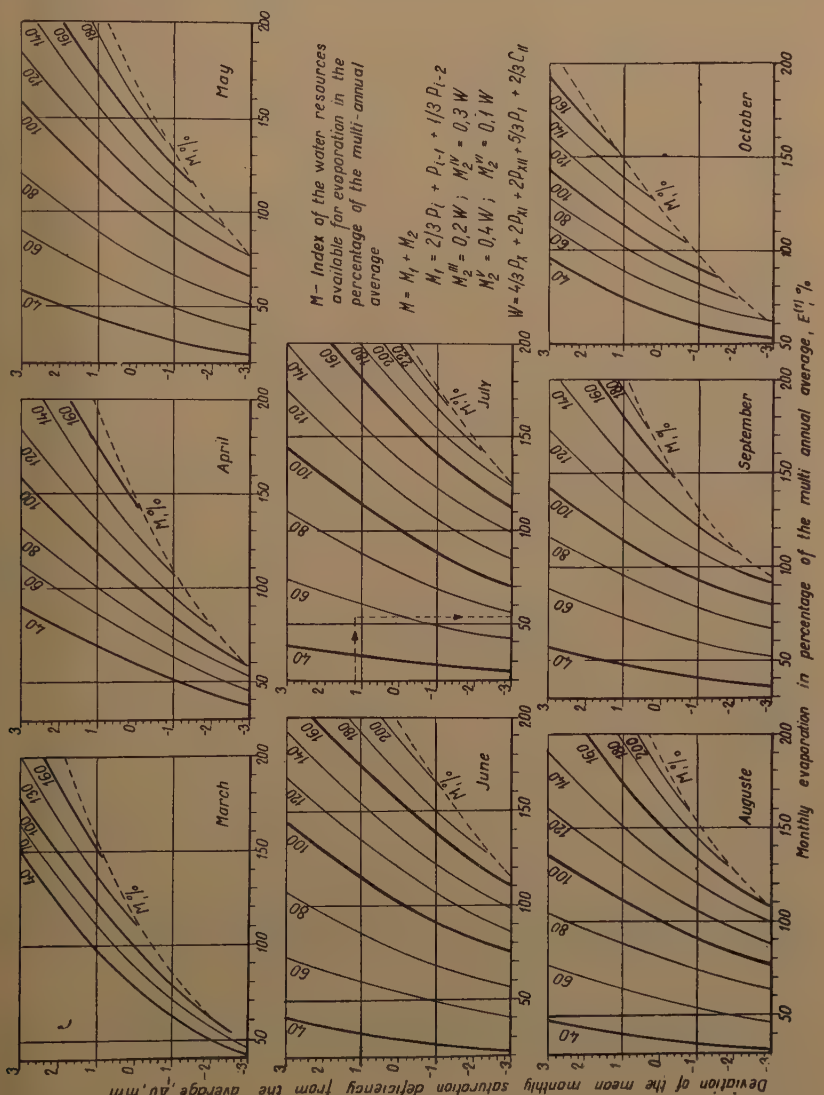


Fig. 6 — Graphs for estimation monthly evaporation on the basis of saturation deficiency data. (For reconstruction the graphs see data in table 1).

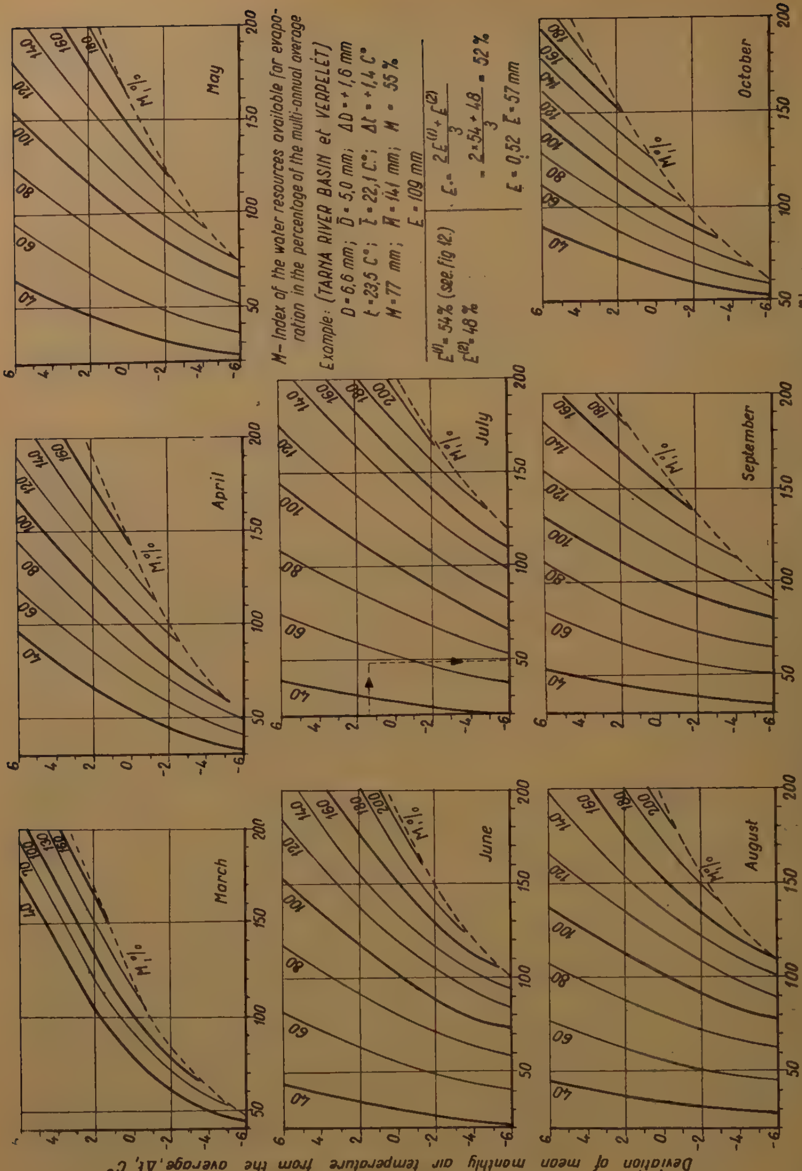


Fig. 7 — Graphs for estimation monthly evaporation on he basis of air temperature data. (For reconstruction the graphs see data in table 2).

Data for the construction monthly evaporation graphs on fig. 6

(Abscissae of the M curves on the axis E, %)

N°	Ordinates of the M curves		Index of the water resources, available for evaporation, M, %																	
			March									April								
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	180	P°
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
1		+ 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	Deviation of the	+ 3	151	166	178	194	202	213	—	—	—	90	110	132	156	186	213	—	—	—
3	mean monthly	+ 2	123	134	146	160	170	181	189	196	200	80	98	117	136	161	185	205	221	—
4	saturation deficiency	+ 1	98	107	117	127	136	147	154	—	156	70	86	102	118	137	157	175	—	185
5	from the	0	77	84	92	100	107	115	—	—	115	60	73	86	100	113	130	—	—	144
6	multi-annual	— 1	61	67	72	78	82	—	—	—	86	51	61	71	81	92	103	—	—	106
7	average,	— 2	50	55	60	64	—	—	—	—	64	42	51	60	68	77	—	—	—	77
8	ΔD, mm	— 3	42	46	—	—	—	—	—	—	46	37	46	53	—	—	—	—	—	56
9		— 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																		
			May									June									
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	180	200	P°
			(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
1		+ 4	—	—	—	—	—	—	—	—	—	40	79	118	157	185	213	—	—	—	—
2	Deviation of the	+ 3	58	86	118	151	177	203	—	—	—	37	71	106	142	168	192	217	—	—	—
3	mean monthly	+ 2	50	76	102	133	156	177	201	224	—	34	64	96	128	151	172	194	215	—	—
4	saturation deficiency	+ 1	43	66	88	116	136	154	175	194	201	31	59	86	113	134	153	172	190	211	—
5	from the	0	36	56	76	100	117	131	148	164	164	28	53	77	100	119	136	151	167	185	194
6	multi-annual	— 1	31	50	67	85	100	111	124	—	129	26	48	70	90	106	120	134	148	162	163
7	average,	— 2	27	44	59	75	87	95	—	—	98	24	45	65	81	96	108	121	133	—	136
8	ΔD, mm	— 3	25	40	54	68	78	—	—	—	79	22	42	60	75	88	99	111	—	—	116
9		— 4	—	—	—	—	—	—	—	—	—	21	40	57	71	82	93	—	—	—	101

TABLE 1 (*continued*)

Data for the construction monthly evaporation graphs on fig. 6

(Abscissae of the M curves on the axis E, %)

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																				
			July											August									
			40	60	80	100	120	140	160	180	200	220	P°	40	60	80	100	120	140	160	180	200	P°
	(1)	(2)	(40)	(41)	(42)	(43)	(44)	(45)	(46)	(47)	(48)	(49)	(50)	(51)	(52)	(53)	(54)	(55)	(56)	(57)	(58)	(59)	(60)
1		+ 4	42	85	125	164	191	221	—	—	—	—	—	48	85	119	148	180	—	—	—	—	—
2	Deviation of the	+ 3	39	76	112	148	173	199	—	—	—	—	—	45	76	108	134	162	191	—	—	—	—
3	mean monthly	+ 2	36	68	99	132	154	177	202	223	—	—	—	43	69	97	121	145	170	199	—	—	—
4	saturation deficiency	+ 1	34	60	87	115	136	157	177	199	218	—	—	41	63	88	110	129	150	172	196	—	—
5	from the	0	31	54	77	100	119	138	157	174	193	207	207	38	58	80	100	116	132	148	167	186	186
6	multi-annual	— 1	29	49	68	86	104	122	139	153	168	—	175	35	53	73	90	105	118	130	143	—	150
7	average,	— 2	27	44	60	76	92	109	123	138	—	—	147	33	50	68	84	96	107	117	—	—	126
8	ΔD, mm	— 3	24	42	56	70	85	100	113	125	—	—	125	32	48	64	77	89	99	108	—	—	109
9		— 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																	
			September									October								
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	P°	
	(1)	(2)	(61)	(62)	(63)	(64)	(65)	(66)	(67)	(68)	(69)	(70)	(71)	(72)	(73)	(74)	(75)	(76)	(77)	
1		+ 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
2	Deviation of the	+ 3	55	88	120	146	173	207	—	—	—	95	111	127	144	160	175	191	205	
3	mean monthly	+ 2	51	79	107	127	151	180	206	—	—	83	99	114	127	142	156	170	176	
4	saturation deficiency	+ 1	48	72	95	113	113	158	180	194	—	74	88	100	112	126	139	—	149	
5	from the	0	44	66	86	100	118	138	155	—	160	66	78	89	100	113	—	—	123	
6	multi-annual	— 1	41	60	78	92	107	123	—	—	132	60	70	81	91	—	—	—	97	
7	average,	— 2	38	56	73	85	98	109	—	—	108	55	65	75	—	—	—	—	76	
8	ΔD, mm	— 3	36	52	67	81	93	—	—	—	97	53	—	—	—	—	—	—	61	
9		— 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

TABLE 2

Data for the construction monthly evaporation graphs on fig. 7

(Abscissae of the M curves on the axis E, %)

N°	Ordinates of the M curves		Index of the water resources, available for evaporation, M, %																	
			March									April								
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	180	P°
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
1	Deviation of the	+ 6	174	185	198	212	223	—	—	—	—	—	96	120	145	168	189	—	—	—
2	mean monthly	+ 4	138	148	159	170	181	193	203	209	216	216	81	120	124	144	163	185	211	—
3	air temperature	+ 2	104	114	123	133	143	155	164	—	—	166	66	85	103	122	138	156	175	187
4	from the	0	77	85	91	100	109	—	—	—	—	119	54	70	85	100	113	128	—	142
5	multi-annual	— 2	60	64	71	77	—	—	—	—	—	83	44	57	70	80	97	—	—	99
6	average,	— 4	51	56	60	—	—	—	—	—	—	62	37	47	57	66	—	—	—	71
7	Δt, C°	— 6	44	48	—	—	—	—	—	—	—	48	33	41	50	—	—	—	—	53

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																		
			May									June									
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	180	200	P°
			(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)
1	Deviation of the	+ 6	64	94	124	154	180	209	—	—	—	41	79	115	154	183	208	—	—	—	—
2	mean monthly	+ 4	53	81	109	135	159	183	—	—	—	38	71	103	135	160	182	207	—	—	—
3	air temperature	+ 2	44	69	94	116	137	158	180	201	213	34	62	91	116	137	156	177	201	223	—
4	from the	0	38	57	79	100	112	132	150	166	166	30	55	79	100	117	132	149	169	184	190
5	multi-annual	— 2	31	47	67	84	98	110	123	—	125	26	48	70	88	101	113	127	140	—	149
6	average,	— 4	26	40	57	73	83	93	—	—	94	23	43	63	78	91	101	113	—	—	120
7	Δ, t C°	— 6	24	37	52	66	76	—	—	—	76	21	41	59	74	85	95	—	—	—	101

TABLE 2 (*continued*)

Data for the construction monthly evaporation graphs on fig. 7

(Abscissae of the M curves on the axis E, %)

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																				
			July											August									
			40	60	80	100	120	140	160	180	200	220	P°	40	60	80	100	120	140	160	180	200	P°
	(1)	(2)	(40)	(41)	(42)	(43)	(44)	(45)	(46)	(47)	(48)	(49)	(50)	(51)	(52)	(53)	(54)	(55)	(56)	(57)	(58)	(59)	(60)
1	Deviation of the	+ 6	37	73	111	144	177	205	—	—	—	—	—	43	75	106	138	167	197	—	—	—	—
2	mean monthly	+ 4	34	65	97	127	156	180	205	—	—	—	—	39	67	97	124	149	175	—	—	—	—
3	air temperature	+ 2	31	58	86	113	137	160	180	202	—	—	—	36	61	88	111	132	154	175	—	—	—
4	from the	0	28	51	76	100	120	141	158	175	195	208	208	34	55	80	100	117	134	152	174	191	193
5	multi-annual	— 2	25	45	66	87	105	124	140	154	167	—	168	32	51	73	91	106	119	133	150	—	154
6	average,	— 4	22	40	59	77	93	109	124	137	—	—	141	30	48	68	84	96	109	120	—	—	128
7	Δt, C°	— 6	19	37	53	67	82	97	110	—	—	—	121	28	46	63	78	90	101	110	—	—	110

N°	Ordinates of the M curves		Index of the water resources available for evaporation, M, %																	
			September									October								
			40	60	80	100	120	140	160	180	P°	40	60	80	100	120	140	160	180	P°
	(1)	(2)	(61)	(62)	(63)	(64)	(65)	(66)	(67)	(68)	(69)	(70)	(71)	(72)	(73)	(74)	(75)	(76)	(77)	(78)
1	Deviation of the	+ 6	53	82	109	133	159	185	—	—	—	90	110	128	146	161	177	192	210	—
2	mean monthly	+ 4	49	72	98	120	145	168	190	—	—	79	96	112	130	143	158	173	187	189
3	air temperature	+ 2	45	65	88	109	131	152	170	188	192	71	86	99	114	127	140	153	—	156
4	from the	0	42	60	80	100	119	137	153	—	160	65	77	88	100	113	—	—	—	122
5	multi-annual	— 2	39	56	75	92	109	124	—	—	135	60	70	79	89	—	—	—	—	94
6	average,	— 4	37	53	71	86	100	113	—	—	114	56	64	72	—	—	—	—	—	76
7	Δt, C°	— 6	36	52	67	81	92	—	—	—	97	54	60	—	—	—	—	—	—	61

points of the diagrams have been tabulated in *Tables 1 and 2*. On the basis of these data the diagrams may readily be reconstructed to any convenient size.

Charts constructed on the basis of the vapor pressure saturation deficiency resp. temperature may be used separately as well. With both data available the most probable value of monthly evaporation will practicably be obtained in the following weighted form:

$$E = \frac{2\,E^{(1)} + E^{(2)}}{3} \tag{11}$$

Investigations into monthly evaporation should preferably be extended to *include every month of the year* (even if a few only are of interest) since the comparison of annual totals computed, on the one hand, by summing up monthly results and, on the other, by the method to be described in the following, offers an opportunity for control.

3. Aids for the estimation of annual evaporation

As already demonstrated during the analysis of monthly evaporation the available amount of water is of decisive importance as far as evaporation is concerned in the eight-month period between March and October. The volume evaporating in these months amounts to from 90 to 92 per cent of the annual total. As can be seen in *Fig. 2.* most values of the diagram lie within the range where the effect of the saturation defficiency is significantly lower than that of changes in available water resources. This is especially true for periods when the evaporative power is high. These were seen to coincide almost invariably with extremely dry months. Data relating to the summer months (May, June, July, August) decisive for evaporation can hardly be found on the right-hand side of the diagram where the effect of the saturation defficiency is predominant. (This statement is not affected by the lack of observation data on evaporation, since the inspection of the distribution of corresponding values D and M leads to similar conclusions.)

An evaluation according to *Fig. 4* may contribute further information to the study of the annual evaporation. For the catchment area at Jasztelek on the Zagyva River the annual average evaporative power has been derived to be 919 mm, i.e., 179 per cent of the actual average evaporation of 514 mm.

These data go to show that under moderate climates the *evaporative power considerably exceeds actual evaporation* (generally by 50 to 100 per cent). Hence the seemingly contradictory statement that as regards annual evaporation no conclusions of even approximate accuracy can be drawn from the evaporative power (vapor pressure saturation deficiency or temperature).

Annual evaporation should therefore be considered in the first instance as *a function of available water volumes* (*i.e., precipitation data*) rather than of the evaporative power, or, more correctly, variations in the latter may be involved only after having considered the sum and monthly distribution of available water volumes.

On the strength of similar considerations the *annual precipitation and its distribution within the year* should be adopted as the primary factors affecting annual evaporation. Since evaporation is relatively greater (and the runoff smaller) in summer than in winter and in the early spring months, the necessity of allowing for the annual distribution of precipitation is obvious. Naturally, in case *runoff records* are also available the investigation should preferably be based not on precipitation data, but on differences (P — R) related to the water year since the latter furnish much more reliable information as to the water volume available for evaporation. Owing to seasonal variations in runoff conditions, differences (P — R) are *to a certain degree*

representative of the seasonal distribution of precipitation as well. The inclusion of the latter (or of differences P — R) as an auxiliary parameter is the more indicated since, beside runoff conditions, infiltration *characteristics* (the annual march of storage) are also affected thereby.

Having thus defined the water volume available for evaporation, the factors influencing the evaporative power (such as vapor pressure saturation deficiency and/or temperature) may be examined. The employment of simple annual averages (annual average saturation deficiency, or mean temperature) is even under such circumstances not advisable. Monthly data of saturation deficiency (or temperature) *should be weighted according to the march of actually available water.* The index M discussed in detail in the foregoing appears to be most convenient for this purpose, since it includes, in addition to the precipitation during the month under consideration, the effect of the precipitation of the two previous months and of winter storage. Further investigations have therefore been founded on the weighted saturation deficiency defined as the sum of values $e_i = D_i M_i$ computed according to Eq. (6) for each month. Thus

$$\epsilon = \sum_{\mathrm{III}}^{\mathrm{X}} D_i M_i \tag{12}$$

and may be referred to as the *coefficient of annual evaporation.*

The evaporative power in the four-month period between November and February has been allowed for in the annual evaporation coefficient given by Eq. (12), the index M being undefined for this period. Considering that the aggregate evaporation during the four month-period in question hardly amounts to from 6 to 8 per cents of the annual total, this simplification—in view of the other uncertainties involved in the investigation—is deemed permissible.

The above-listed factors affecting annual evaporation may be comprised in the relation, containing five variables

$$E = f(P, P(t), R, \epsilon) \tag{13}$$

wherein $P(t)$ denotes the variation of precipitation with time (the distribution within a year).

A solution of the above relation has here again been attempted by resolving it into a set of three-variable graphical correlations [5]. Evaluation and comparison of a number of alternatives have led to the following set of relations:

$$E^{(1)} = f(P, P_{\mathrm{IV-IX}}) \tag{14}$$

$$E^{(2)} = f(P - R, P_{\mathrm{IV-IX}}) \tag{15}$$

$$E^{(3)} = f(P, \epsilon) \tag{16}$$

$$E^{(4)} = f(P - R, \epsilon) \tag{17}$$

$$E^{(5)} = f(\epsilon, M_{\mathrm{V-VIII}}) \tag{18}$$

In these relations *every quantity has been substituted in the percentage of the long-period average.*

The seasonal (monthly) distribution of precipitation has been characterized —as can be seen— by two parameters ($P_{\mathrm{IV-IX}}$ and $M_{\mathrm{V-VIII}}$). The first serves essentially to represent differences between summer and winter precipitation, while the latter is used to put weighted emphasis on the four months considered critical as far as evaporation is concerned.

In selecting the structure of individual relations care has been taken to enable an at least approximating solution even if some of the data are missing. Relation (14)

contains but *precipitation data*, whereas *precipitation and runoff data* feature in relation (15). The remaining three relations can be applied only by the evaluation of vapor pressure saturation deficiency data.

Aids have been constructed by using the method developed previously for the determination of monthly evaporation. Values of the latter have been computed for four catchment areas in Hungary (see *Fig. 8.*) and for an aggregate period of 110 years. Annual evaporation from each catchment area has been obtained as the sum of monthly values.

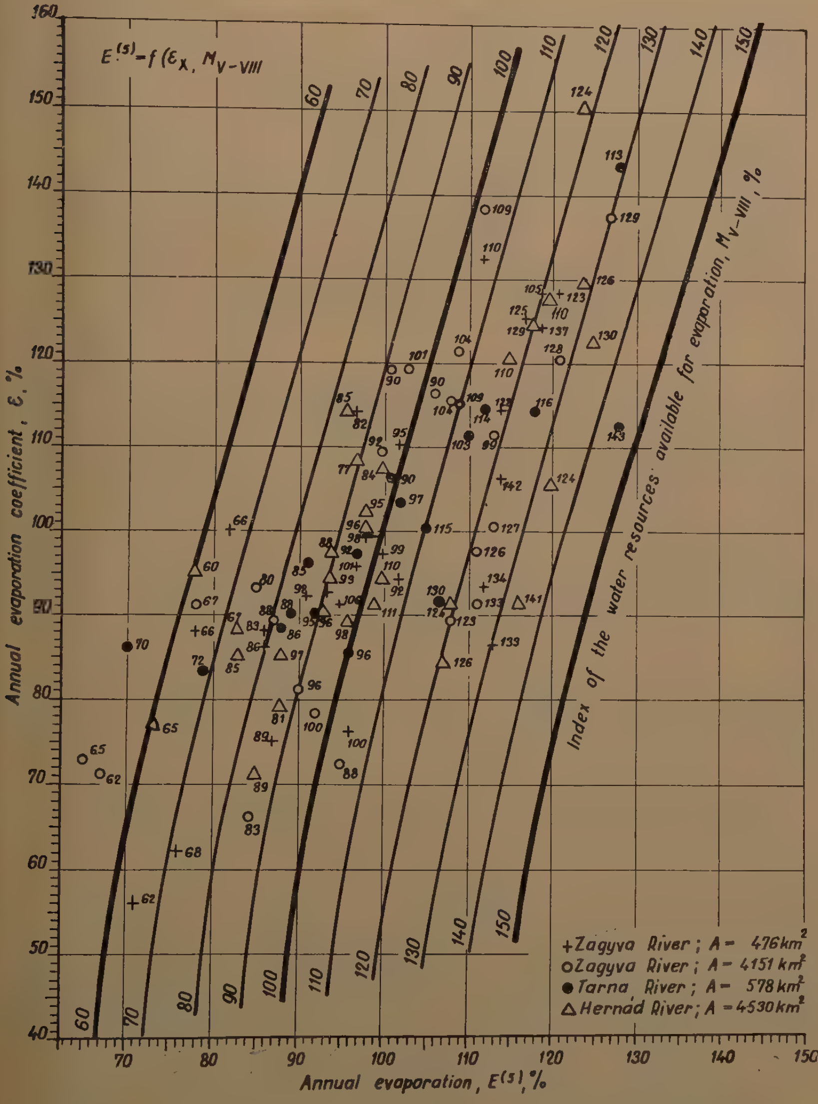


Fig. 8 — Example for the construction of annual evaporation graphs.

Data thus obtained have subsequently been plotted according to the three-variable relations (14) and (18). The abscissae represent evaporation data, the ordinatae the first independent variable, while values of the second independent variable are marked beside the points. As an example data plotted according to relation (18) are shown in *Fig. 8.*

Values noted beside the points revealed on all five figures a fairly definite pattern and the isometric lines could readily be plotted. In order to facilitate construction, different colours have been used on the original charts to mark groups of different intervals in value *M*. Isometric lines were drawn along the equalizing lines resp. separating lines of differently colour groups. Three-variable graphs constructed for the determination of annual evaporation are shown in *Fig. 9.*

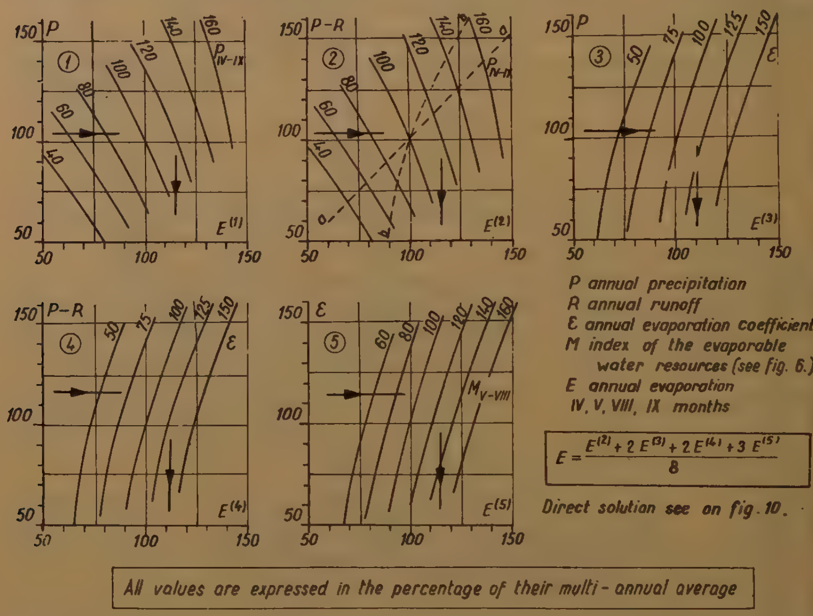


Fig. 9 — Three variable graphs for estimation annual evaporation in the case of lack in basic data.

Attempts have been made to support resp. to check individual steps in the course of construction by *considerations of physical nature.*

One of the initial assumptions was that the 100 isometric should pass in each diagram through the points determined by the 100 mark on the co-ordinate axes.

Isometric lines in *Fig. 9-1* based exclusively on precipitation data are not parallel. The 40 isometric encloses an angle of about 45 degs. with the vertical axis, while that enclosed by the 140 isometric and the latter is no more than 15 to 20 degs. The increasing slope of the isometric lines can be explained by the fact, that the significance of precipitation stored in the winter (*i.e.* of annual precipitation) diminishes as the relative summer precipitation increases. The very same effect is indicated by *Fig. 9-2* representing the simultaneous influence of precipitation and runoff.

Isometric lines in *Fig. 9-1* convey the suggestion that for *any given summer precipitation annual evaporation reduces with increasing annual precipitatian volume.*

This conclusion may seem erroneous at first glance but this negative effect of winter precipitation can be explained by the following two considerations:

The precipitation volume necessary to meet evaporative power in winter is always available, consequently any increase in precipitation first recharges storage then supplies runoff. It is therefore obvious that winter evaporation may not be increased by precipitation.

It remains to be answered why—for any given summer precipitation—summer evaporation instead of increasing even decreases with increasing *winter precipitation.* Winter runoff from the area considered is wasted definitely (at least in so far as the annual water balance is concerned) and has, consequently, no bearing upon summer evaporation. Precipitation stored on the area supplements the water resource available for summer evaporation (as already pointed out in dealing with index M_2) on the one hand, and, on the other, contributes to the runoff coefficient occurring in the spring and early-summer months. Summer evaporation will be enhanced by the first circumstance, yet will be reduced by the second. Pending prevailing conditions, the latter effect will prevail. This phenomenon is especially conspicuous if a winter with abundant precipitation is followed by an extremely dry summer period. A great portion of spring rainfall concurrent with snow-melt will in such cases be consumed by runoff as a consequence of low evaporative power and high runoff coefficient in this period and will thus be lost for evaporation. On the other hand increased volumes of water precipitating during April and May after a dry winter may be stored in the upper soil layers and carried over to the summer season, supplying thus summer evaporation.

Fig. 9-2 shows the storage effect of the drainage areas as a result of which the annual march of evaporation follows that of the P — R differences with a considerable lag only. As is to be seen from *Fig. 9-2* a reduction of the annual and summer precipitation to half of the long-period average entails a decrease of but 14 per cent in annual evaporation. With an annual precipitation 1,6 times the average, evaporation increases by 30 per cent only (see curve $b - b$). Without natural storage, annual evaporation could vary according to the relation $E = P - R$ as indicated by the curve $a - a$. The storage effect of natural drainage areas is characterized by the difference between curves $a - a$ and $b - b$. As revealed by the trend of these curves the effect of storage is more pronounced in years of extreme precipitation conditions. Under moderate climates annual evaporation in extremely dry years may substantially exceed annual precipitation.

The pattern displayed by points in *Figs.* 9-5 and 8 respectively shows *precipitation conditions of the four months* adopted as parameters to be critical for annual evaporation. The annual distribution of precipitation being reflected to a certain degree also by the annual evaporation coefficient, the considerable scatter of points with the same ordinates and their rather regular arrangement according to M_{V-VIII} values enhances the critical importance of the four summer months.

* * *

The foregoing and similar physical considerations have been relied upon for control and information during the design of charts constructed on the basis of empirical data. In the course of investigations into applied hydrology purely theoretical, mathematico-physical considerations have in several instances failed to yield results of *practical value* unless combined with *empirical relations* deduced from phenomena observed in nature (i.e., reconstructed from observation data).

On the other hand, as demonstrated by the foregoing examples, formulae and charts arrived at by statistical methods remain dead unless corroborated by theoretical considerations.

All the statistical data constitute a lifeless clutter of information to be regarded with utmost suspicion. Groups of points plotted during the construction of charts could be compared to an orchestra missing the guidance of the conductor: a cacophony of clear and dissonant sounds, of voices galopping forward or lagging behind. *The mental effort inquiring into causative interrelations of the phenomenon* could be symbolized by the baton of the conductor creating order and harmony by unravelling the underlying natural law as the representative isometric lines emerge.

* * *

In order to estimate annual evaporation by the aid of Eq. (13) the component three-variable relations providing the solution must be interrelated, i.e., the weighting coefficients s_i furnishing the required average

$$E = \frac{s_1E^{(1)} + s_2E^{(2)} + s_3E^{(3)} + s_4E^{(4)} + s_5E^{(5)}}{s_1 + s_2 + s_3 + s_4 + s_5} \tag{19}$$

established.

The accuracy of interrelation has been established from the statistics of deviations compiled for all of the 110 year used in the investigation.

Results obtained may be resumed in the following:

1. *With only precipitation data available*, the estimated value of annual evaporation (the use of *Fig. 9-)1* may involve a probable error of $\pm$ 10 per cent.

2. *The inclusion of runoff data* (the use of *Fig. 9-2*) hardly increases the accuracy attainable (for the terrain investigated in Hungary the increase is but 1 per cent).

The negligibly small beneficial effect of the inclusion of runoff data on accuracy may be explained by the fact that the annual runoff coefficient on catchment areas in Hungary is very small (from 10 to 15 per cent on the average).

3. With data on the *vapor pressure saturation* defficiency also available *Fig. 9-5* should preferably be used. In this case a probable error of 3,1 per cent should be allowed for.

4. If it is intended to attain *extreme accuracies*, the simultaneous use of *Figs. 9-2, 3, 4* and *5*, and the computation of the weighted mean

$$E = \frac{E^{(2)} + 2E^{(3)} + 2E^{(4)} + 3E^{(5)}}{8} \tag{20}$$

will yield a mean error of 2,9 per cent.

5. *Maximum errors* that may occur are from 2,5 to 3 times the mean error.

A direct solution of Eq. (20) may be attained by the coaxial correlation illustrated in *Fig. 10*. The chart has been constructed on the basis of the three-variable relations according to *Fig. 9* by I. Zsuffa (9).

In the above correlations the sum of evaporation data computed separately for every individual month has been adopted as actual annual evaporation. It has been demonstrated that by using *Fig. 9-5* or *Fig. 10* the annual total may be established *directly* though with a probable error of round 3 per cent. Therefore, depending on the nature of the problem under consideration, the computation of monthly values may be omitted. On the other hand with monthly values established the arithmetic mean computed from the sum of the latter and from the value obtained directly may be adopted as the *most probable value of annual evaporation*. The application of this method naturally involves the necessity of reducing monthly values according to the annual total.

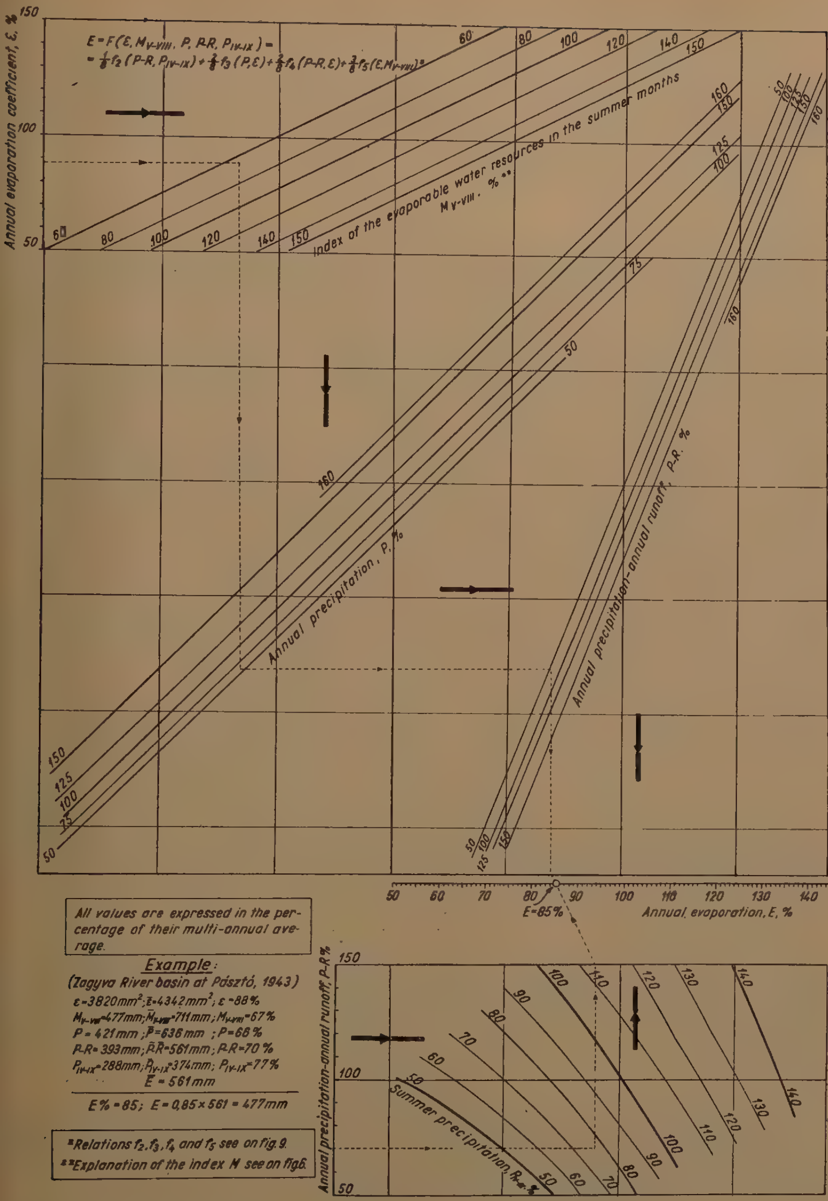


Fig. 10 — Graph for determination annual evaporation on the basis of precipitation, runoff and vapor pressure saturation deficiency data. (The graph was constructed on the basis of the three variable relations on fig. 9. by I. ZSUFFA).

4. Characteristic values of evaporation from large areas

For the solution of practical problems it will often suffice to determine the characteristic evaporation values, *of averages and of extremes*. The application of the above graphs serving purposes of detailed investigations presumes the knowledge of long-period evaporation averages for the year and for individual months.

4-1. *Long-period averages*

The only reliable data on land evaporation is the long-period average of annual evaporation, which can be established as the difference between average precipitation and runoff. Values thus obtained may be entered on maps ([4] and [8]).

The seasonal distribution of evaporation, i.e., evaporation averages for individual months are generally computed by proportioning numbers determined on the basis of lysimeter observation records. These proportions may be considered characteristic for a narrow environment only, even if uncertainties resulting from discrepancies between lysimeter observations and natural evaporation conditions are disregarded. In remote areas the distribution of atmospheric humidity and of precipitation in the year may be entirely different. In such cases the mechanical application of the proportion-numbers may introduce more serious errors than the use of indirect methods allowing for climatic conditions. In Hungary, for want of lysimeter observations, similar methods must at present be relied upon.

For the development of indirect methods climatic conditions properly characterizing evaporation conditions should be established first. *Monthly evaporation coefficients* e = DM applied previously in connection with Eq. (6) appear as most convenient for this purpose since they account for both main characteristics of land evaporation, i.e., evaporative power and available water resources.

Monthly evaporation coefficients are rendered especially suitable for the said purpose by the boundary condition governing the determination of index M_2. According to this condition a close agreement between evaporation coefficients established for the instanced German lysimeter stations and the observed monthly distribution of actual evaporation is required for the eight summer months. The evaluation of the effects of winter storage according to the above condition—represented by the coefficients in Eqs. (5)—permits the D.M. sets to express such evaporation features as would remain unexplained by vapor pressure saturation deficiency and precipitation alone.

a) The computation of average monthly evaporation on the basis of evaporation coefficients is illustrated in *Table 3* compiled by using data obtained for the catchment area of the Sajo River, Hungary. The difference of the annual precipitation and runoff listed under items 1 and 2 respectively yields the long-period average annual evaporation:

$$\bar{E} = \bar{P} - \bar{R} = 660 - 158 = 502 \text{ mm}$$

Monthly mean saturation deficiency are listed under item 3. Evaporation in the four winter months can directly be obtained from graphs shown in *Fig. 1*. Subtracting these from $\bar{E}$ the aggregate evaporation for the eight summer months is obtained:

$$E_{summer} = E - (E_{XI} + E_{XII} + E_{I} + E_{II}) = 502 - 27 = 475 \text{ mm}$$

The computation of monthly evaporation coefficients according to Eq. (3) resp. Eqs. (4) and (5) follows next. Indexes M_1 and M_2 listed under items 4 and 5 respectively represent water resources available for evaporation (item 6). The products of corresponding D and M values from items 3 and 6 respectively are the

TABLE 3

Determination of the mean monthly evaporation

Sajo River basin at Felsozsolca (A = 6445 km²), 1921-40

Elements of the water balance				Months												Water year
				Winter				Summer								
				XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	
Precipitation, P		mm	(1)	52	34	29	28	40	48	78	88	68	79	54	62	660
Runoff, R		mm	(2)	14	12	10	11	28	24	19	15	8	5	5	7	158
Vapor pressure saturation deficiency, D		mm	(3)	0,7	0,5	0,5	0,7	1,4	2,6	3,9	4,6	5,7	4,7	3,1	1,7	
Index of the water resources available for evaporation	land surface M_1	mm	(4)					64	81	113	152	160	149	138	121	
	root zone M_2	mm	(5)					66	100	132	33					331
	$M = M_1 + M_2$	mm	(6)					130	181	245	185	160	149	138	121	
Evaporation coefficient, $\epsilon = DM \times 10^{-2}$		mm²	(7)					1,8	4,7	9,5	8,5	9,1	7,0	4,3	2,0	45,9
Evaporation, E		mm	(8)	9	5	6	7	18	48	96	86	92	71	44	20	502

$\bar{E} = \bar{P} - \bar{R} = 660 - 158 = 502$ mm. $\qquad \bar{E}_{summer} = \bar{E} - \bar{E}_{winter} = 502 - 27 = 475$ mm.

$W = 4/3\, P_X + 2\, P_{XI} + 2\, P_{XII} + 5/3\, P + 2/3\, P_{II} = 92 + 104 + 68 + 49 + 18 = 331$

$M_1^{(i)} = 2/3\, P_i + P_{i-1} + 1/3\, P_{i-2}$ $\qquad M_2^{III} = 0{,}2\, W = 66$ mm; $M_2^{IV} = 0{,}3\, W = 100$ mm;

$E_s = \dfrac{E_{summer}}{\epsilon} = \dfrac{475}{45{,}9} = 10{,}3$ mm/mm² $\qquad M_2^{V} = 0{,}4\, W = 132$ mm; $M_2^{VI} = 0{,}1\, W = 33$ mm

monthly evaporation coefficients (item 7) whose sum

$$\epsilon = \sum_{III}^{X} DM = 45{,}9 \text{ mm}^2$$

Specific evaporation E_s pertaining to unit evaporation coefficient is obtained as the ratio of aggregate summer evaporation and of value ϵ

$$E_s = \frac{E_{summer}}{\epsilon} = \frac{475}{45{,}9} = 10{,}3 \text{ mm/mm}^2$$

In possession of the specific evaporation value the product $e\ E_s$ yields the evaporating volume for each summer month direcly (item 8).

b) Computations involving the use of the evaporation coefficient are rather lengthy and presume the knowledge of the long-period average of the vapor pressure saturation deficiency. Practical requirements may often be met by the aid shown In *Fig.* (*11*) featuring *monthly average evaporation as the function of monthly mean temperature and of annual average evaporation.* Curves illustrated in the graph have been established by detailed methods for several Hungarian and German stations. The conspicuous change in slope of these curves illustrates the circumstance that in

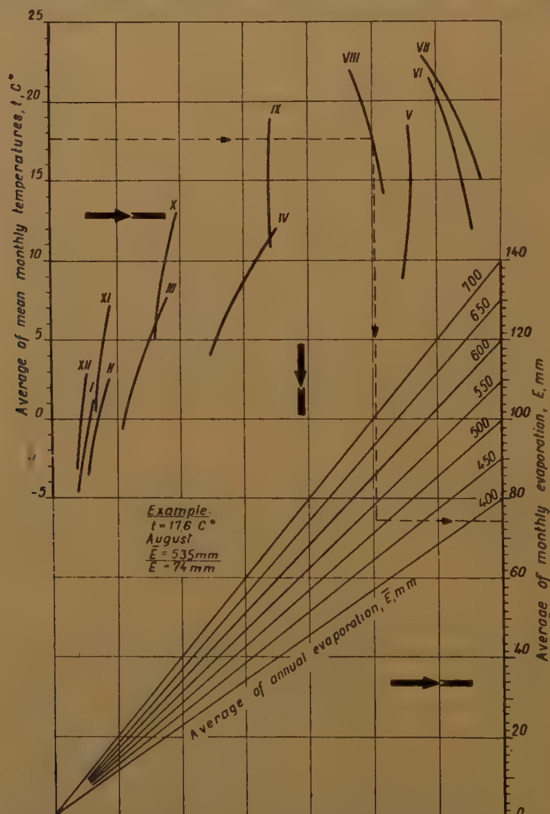


Fig. 11 — Graph for estimation mean montly evaporation from large areas. (The graph was constructed on the basis of data from Hungary and Germany).

plain territories having higher mean temperatures the lack in available water resources is to be felt much earlier and to a more serious degree than in mountainous areas.

In order to reduce discrepancies resulting from faulty readings and from irregular distributions of temperature over the territory, evaporation should preferably be determined by using the graph in *Fig. 11* for *every month* even if a few only are included in the investigation. Agreement between annual evaporation obtained as the sum of values furnished by the graph and the initial value thereoff (computed as the difference $\overline{P} - \overline{R}$) may provide a possibility of control in so far as the two above

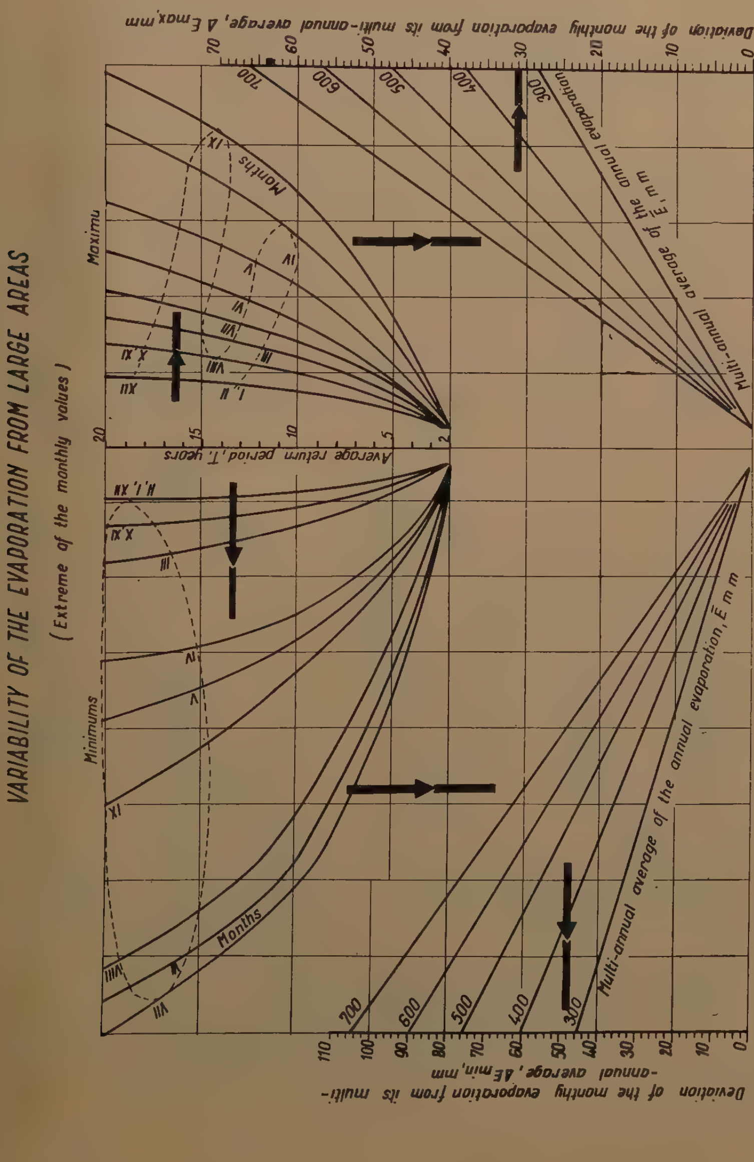


Fig. 12 — Variability of monthly evaporation from large areas shows clearly the effect of the lack in water resources available for evaporation in the summer months. (Constructed by P. VALKO).

sources of errors are concerned. (Fully reliable control cannot be obtained in this case either, since the annual total is involved in readings from the graph.)

4-2. *Characteristic extremes*

Aids serving the determination of *extreme values of monthly evaporation* (maxima and minima corresponding to a required probability may be found elsewhere at a

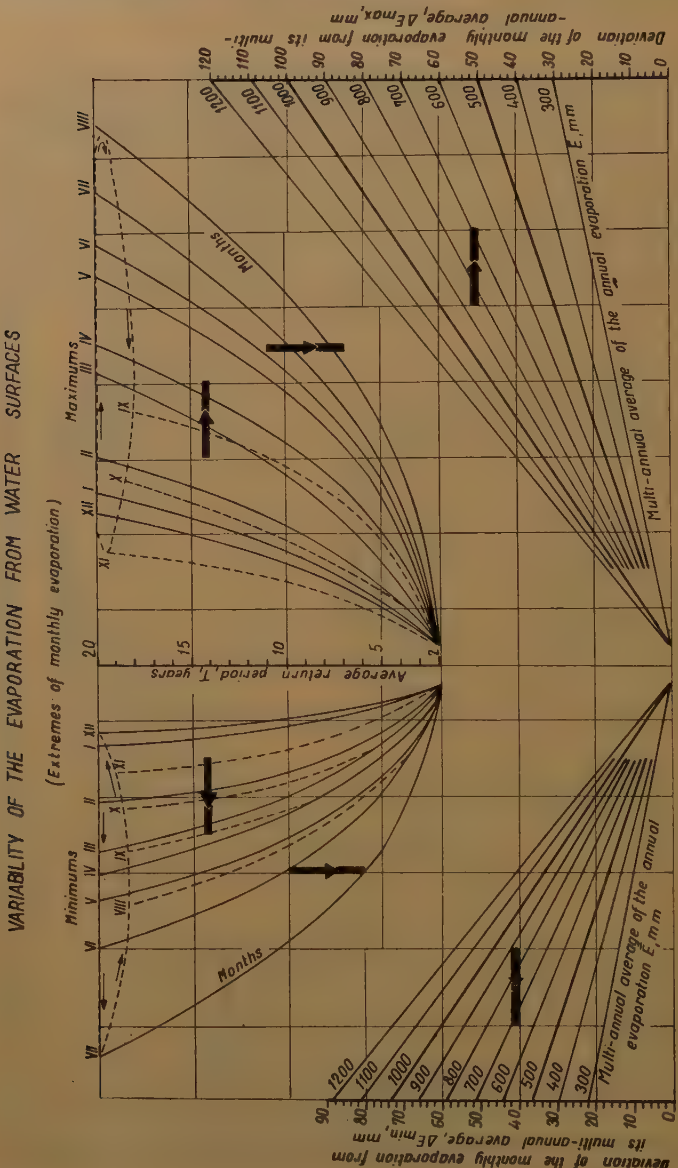


Fig. 13 — Variability of monthly evaporation from water surfaces shows continuous distribution in the year. (The graph was constructed by P. VALKO).

scale and to a degree of accuracy meeting practical requirements ([8]). Physical laws revealed by the graphs are illustrated in *Fig. 12.* comprising the diagrams used in computing monthly maxima and minima in reduced size.

Effects of *lock in available water resources* in the summer months are clearly shown in *Fig. 12.* Owing to this effect the curve connecting successive months shows at the side of maxima a marked contraction between April and September. The lack of available water resources in the summer months practically severs the upper section of the distribution curve. Naturally, on the side of minima no such effect can be observed. Curves representing individual months run continuous succession according to the order of magnitude and natural variability of data.

The above feature of *Fig. 12.* will become even more conspicuous when compared with results of a similar study on the *variability of evaporation from water surfaces.* (See *Fig. 13.*) Since the water volume required to match evaporative power is in this case always available, the curves representing individual months form a continuous succession on the side of maxima as well.

The collation of the right sides of *Figs 12* and *13* may provide a *climatic characteristic* as far as humidity conditions are concerned. For nothern regions having humid climates a steady succession of curves, without intermediate recess, may be expected. The drier the climate of the region, the more pronounced the summer contraction of curves indicating summer evaporation and the greater the discrepancy in relation to corresponding curves of evaporation from water surfaces.

The determination of characteristic extremes for a period of several months by the simple summation of values established for individual months is not permissible. Statistical elaboration should be applied to each period separately. Graphs for the determination of characteristic extremes for *annual* and half-year evaporation are given in the publication of the Institute referred to previously ([8]).

REFERENCES

([1]) KALWEIT, H. Der Wasserhaushalt. *VEB Verlag Technik*, Berlin, 1953.

([2]) LASZLOFFY W. A fajlagos lefolyas sokévi atlaga Magyarorszagon és a hidrologiai hossz-szelvények. Mean Annual Runoff in Hungary and Hydrologic Longitudinal Sections. (*Vizügyi Közlemények*, 1954. No. 2. (In Hungarian with French summary).

([3]) LINSLEY-KOHLER-PAULHUS: Applied Hydrology. *Mc Graw-Hill*, New York, 1949.

([4]) SZESZTAY K. Segédletek a területi parolgas meghatarozasara. *Beszámoló a Vizgazdálkodási Tudományos Kutató Intézet 1956. évi munkájáról.* (Aids for the Estimation of Evaporation from large areas. *Annual Report, 1956, Research Institute for Water Resources.*) Müszaki Kiadó, Budapest, 1957. (In Hungarian with english summary).

([5]) SZESZTAY K. Some methodical problems of flood forecasting in drainage basins of great extension. *Publication No. 42. de l'Association Internationale d'Hydrologie, Symposia Darcy*, Dijon, 1956. III.

([6]) UHLIG S. Der mittlere Jahresgang des ausschöpfbaren Bodenfeuchtegehaltes. *Die Wasserwirtschaft*, Jahrgang 46. Heft 5. Seite 121, 1955.

([7]) Research Institute for Water Resources. *Vizgazdálkodási Tudományos Kutató Intézet* : A természetes párolgás. (Natural evaporation). *Manuscript.* Budapest, 1957. (pp. 159, 80 fig. and 20 tables.) In Hungarian). Compiled by K. SZESZTAY.

([8]) Research Institute for Water Resources. *Vizgazdálkodási Tudományos Kutató Intézet.* Magyarország Hidrologiai Atlasza. II/2. füzet. Hómérséklet és parolgas./Hydrologic Atlas of Hungary Vol II/2. Temperature and Evaporation. (In Hungarian).

([9]) ZSUFFA I. Az arvizi elórejelzési segédletek szerkesztésének néhany elméleti kérdése. *Beszámoló a Vizgazdálkodási Tudományos Kutató Intézet 1956. évi munkájáról.* (Same Theoretical Problems of Constructing Coaxial Graphs for Flood-Forecasting *Annual Report, 1956, Research Institute for Water Resources*). Müszaki Kiadó, Budapest, 1957. (In Hungarian with French summary).

THE INFLUENCE OF INCREASING AGRICULTURAL PRODUCTION ON WATER UTILIZATION OF CULTIVATED CROPS

OSTROMECKI JERZY
Agricultural Meliorations and Grassland Institute Warsaw — Poland

SUMMARY

In the following paper the author presents the problem of changes in field evaporation which can take place as agricultural production is intensified and crop yields increase.

Comparison of data based on literature, and concerning field evaporation determined by means of two various methods (water balance method and energetic balance method) shows, that both methods are sufficiently in agreement in characterizing phenomena. In view of the fact that more available material is based on the water balance method, further deliberations in this study are based on lysimetric and field observations.

Elaboration of material from investigations conducted by the author render it possible to determine a mathematical form for illustrating the influence of produced total amount of plants on changes in field evaporation, providing conditions decisive for evaporation i.e. agrotechniques, soil moisture, etc. change simultaneously. The appropriate formula is as follows:

$$\frac{V_n}{V} = \frac{V_0'}{V_0}\left[\frac{\beta_2}{\beta_1}\sqrt[3]{n^2} - \frac{V_0}{V}\left(\frac{\beta_2}{\beta_1}\sqrt[3]{n^2 - 1}\right)\right]$$

in which:

V = denotes field evaporation at crop yields accepted as one,

V_n = denotes expected field evaporation at crop yields n-times greater.

The values of coefficients according to experimental data are as follows:

$$\frac{V0}{V} = 0.47 - 0.74 \text{ et } \frac{V_0'}{V0} = 0.73 - 0.82$$

$$\frac{\beta_2}{\beta_1} = 1.2 - 1.5.$$

Arithmetical computations according to this formula showed that for instance doubling yields entails increased evaporation within limits of only 1.09 — 1.31. It is possible, by applying proper agrotechniques, to obtain 25 to 35 % higher yields without increasing field evaporation.

Analytical data was compared with the results of hydrological data obtained in one of the river basins, and showed sufficient conformance of results.

1. INTRODUCTION

Utilization of water by cultivated areas during the period of vegetation consists of the following positions: *a*) plant transpiration, *b*) partial evaporation of rainfall directly from the surface of plants, *c*) soil evaporation.

The sum of these losses in relation to a unit of areas constitutes field evaporation i.e. evapotranspiration. In order to plan the water balance in a given basin, it is necessary to know existing field evaporation, and expected evaporation after meliorations and after increasing agricultural production. Field evaporation not only depends upon natural climatic and soil conditions, and the kind of vegetation, but also to a considerable degree upon melioration and agricultural measures, hence it can be regulated.

Utilization of water by the vegetation, determined according to existing field

evaporation, cannot be identified with water requirements of plants. Water requirements, or in other words the real minimum amount of water sufficient for the production of plant matter. are closely connected with ecological conditions and tillage; hence transference of observed unit outgo (in relation to a cultivated area or crop) to other conditions must be carried out with great care.

An analysis of each of the components of field evaporation based on numerous data from literature, leads to the following conclusions:

A. Increased transpiration is not always necessary for obtaining higher yields. This relates both to the transpiration coefficient (in relation to a unit of produced plant matter), as also to total transpiration. Usually as yields increase, for instance due to better cultivation, unit water utilization decreases, and — by changing for example air humidity conditions, it is possible to decrease total transpiration from the whole field. Transpiration is greatly influenced by fertilization, and thus for example potassium decreases it. Due to the fact that transpiration is also a regulator of the microclimate surrounding the plant, total transpiration should not be excessively limited. Agricultural measures should tend to create conditions for decreasing the transpiration coefficient, or in other words transpiration per unit of matter produced.

B. Increased plant coverage of the soil favors direct evaporation of part of the rainfall from the surface of plants. Especially small amounts of precipitation reaching 1 - 2 mm might never reach the soil. Direct evaporation, however, is not totally lost, as it influences humidity of the microclimate, thereby forming the conditions of transpiration.

C. Increased crop yields, through greater shading and a specific microclimate within the plant cover, limit surface evaporation from the soil, and can to a certain extent limit transpiration.

Properly applied agricultural measures play a major role in soil evaporation by changing unproductive evaporation into productive one i.e. through plant transpiration.

2. Methods of Studying Field Evaporation

As can be seen from the above, field evaporation is a complex process in which specific components are mutually dependent. Hence determining field evaporation only on the basis of specific components, as is frequently done in literature, is of no avail. In studies on water balances, evaporation should be considered as a whole, taking into account—of course—the necessary analysis of components.

Changes in field evaporation are investigated in agriculture by means of two methods. The older, purely experimental which can be called the hydrological method consists of computing the water balance elements of the plant as such, either of the plant covering as a whole in pots, lysimeters, plots, fields or whole basins. A newer method is based on the energetic balance of the field by determining outgo of heat for evaporation and atmospheric exchange.

Investigations based on the first type, having a smaller theoretical background, supplied a good deal of experimental material; investigations of the second type, although theoretically more accurate, dispose of less abundant experimental material than the previous. So far Poland has but little data on field energetics, and that material which is available, is insufficient for a synthetic analysis.

In view of the above, further considerations will be based on experimental methods, and results checked as far as possible by comparing with results obtained in the Soviet Union within the field energetic method.

3. Changes in Field Evaporation under the Influence of Plant Matter Increase

Observations on evaporation conducted by means of the hydrological method show that in general the sum of evaporation increases as crop yields increase, providing air, soil and other humidity conditions remain unchanged. Evaporation increase, however, takes place much more slowly than green matter increase. Even in controlled conditions, notwithstanding increased plant matter production, evapotranspiration is smaller.

It can be assumed on the basis of author's investigations, that field evaporation as a resultant of three components, can be presented in the following form:

$$V = V_0[1 + f(Q)], \quad (1)$$

in which:

V — field evaporation during a given period per unit of area covered with vegetation,

Q — crop yields at the end of observations per unit of area,

V_0 — field evaporation which would have taken place during the same period of time per unit of area but at a minimum yield, hence at $Q = 0$.

Expression V_0 is variable, depends upon precipitation, the state of soil moisture content air evaporation capability (air moisture deficiency), kind of cultivation etc.

The expression $1 + f(Q)$ is also variable, increases with yields, and can be various for various crops.

The range of the presented formula is limited to values Q and V_0 considered in this experiment. Extrapolation beyond this range cannot be certain, as observations illustrate only part of the curve showing the course of evaporation phenomena.

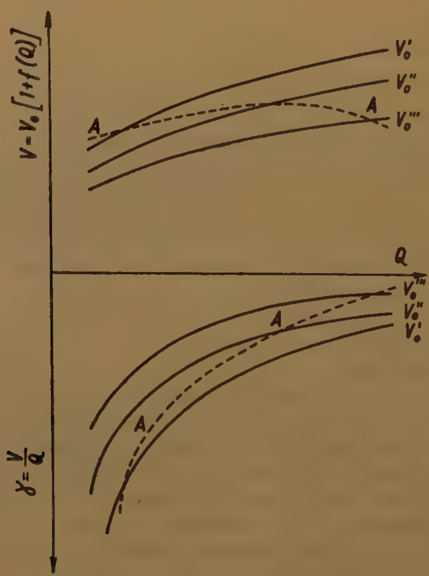


Fig. 1 — Dependences of field evaporation (V) and unit water utilization (γ) upon the yields of crops (Q).

By dividing both sides of the formula (1) by crop yields Q, water utilization per yield unit is obtained

$$\Upsilon = \frac{V}{Q} = \frac{V_0[1 + f(Q)]}{Q} \qquad (2)$$

For applied functions, unit utilization always declines as yields increase if V_0 = const.

Formulae (1) and (2) are graphically presented in Fig. 1.; variable values $V_0 = V_0', V_0'', V_0'''$ were accepted for the determined expression $[1 + f(Q)]$, hence giving a bundle of curves.

If V_0 = const, then evaporation increases with yields. If however V_0 is changed parallel to crop yield increases (sequently V_0', V_0'', V_0''' etc.), for example by applying better agricultural measures, introducing tree - shelter belts, etc., then a decline in evaporation can be obtained notwithstanding crop yield increases. This phenomenon is expressed in Fig. 1 by the broken line (A — A), constituting a certain trajectory for a given bundle of specific curves.

Inasmuch as the above described process of evaporation changes was described on the basis of material obtained by applying the hydrological method, results should be compared with results of the energetic method. Figs. 2, 3 and 4 present graphs drawn up on the basis of tables from the study by Preobrazenski ([10, 11, 12]), who defined the inter-relation between evaporation and yields of wheat, lucerne and sugar beets at various levels of agriculture and irrigation on the basis of energetic balance computations.

As can be seen by comparing Fig. 1 and Figs. 2, 3, 4, the results reached by means of the hydrological method are in agreement with those based on the energetic method. Hence the following statements can be assumed as being correct:

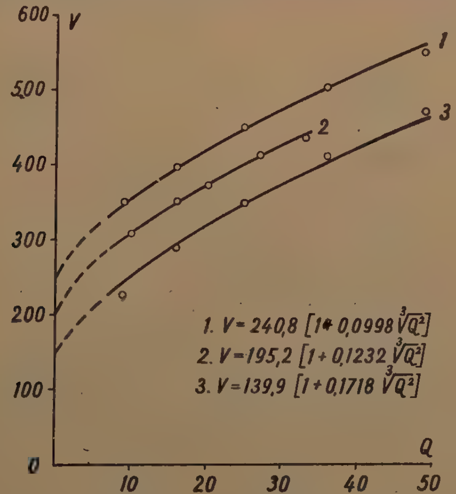


Fig. 2 — Evaporation of wheat field in dry regions.
Curves computed and defined on the basis of data published by Preobrazenski for the Soviet Union
V — evaporation in mm
Q — yields of grain in q/ha
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management.

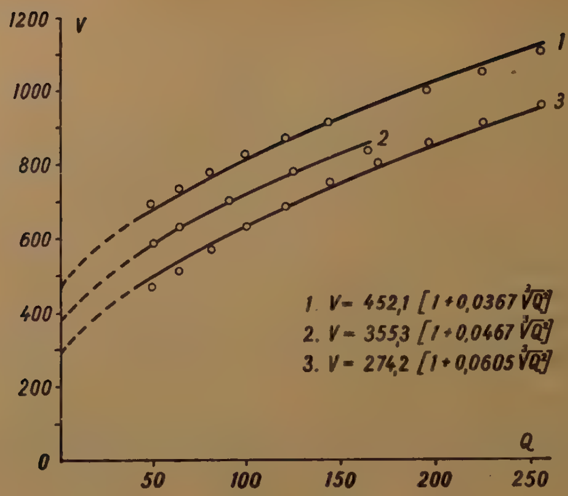


Fig. 3 — Evaporation of alfa-alfa field in dry regions
Curves computed and defined on the basis of data published by Preobrazenski for the Soviet Union
V — evaporation in mm
Q — yields of hay in q/ha
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management.

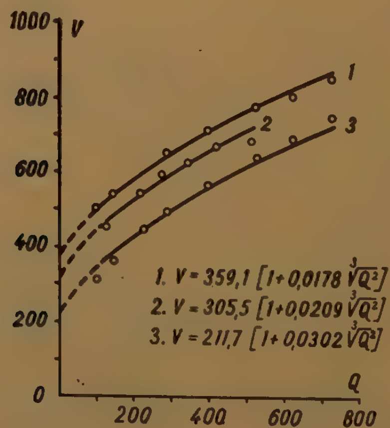


Fig. 4 — Evaporation of sugar beet field in dry regions
Curves computed and defined on the basis of data published by Preobrazenski for the Soviet Union
V — evaporation in mm
Q — yields of roots in q/ha
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management.

1. Field evaporation depends, among others, upon the level of crop yields.

2. At unchanged soil, climatic and agricultural conditions, evaporation increases with increasing crop yields.

3. Evaporation increase takes place much more slowly than increase of plant matter causing the former.

4. The level of agriculture and proper water economy are of significant importance for the extent of evaporation; due to these factors economy in water utilization can reach—for example in irrigated regions—20% (not taking into account losses in the irrigation network).

5. It is possible, through proper management, to decrease to a certain extent outgo for evaporation in spite of increased yields.

It should also be mentioned that not all scientists agree with the statement that evaporation increases with yields. Thus for example Alpatiew (1) is of the opinion that these phenomena are independent in conditions of optimum humidity, and endeavors to prove his statement by citing a number of experimental figures. An analysis of this data contained in Table 76 of Alpatiew's work, and graphically presented in Fig. 5, does not agree with conclusions reached by the above mentioned author. The inter-relation can here be seen between the amount of water utilized and production of plant matter; this inter-relation corresponds in outline to that obtained by Preobrazenski, remembering however that Alpatiew's data relate to South Russia and the Ukraine, while Preobrazenski's to Central Asia (Kazachstan), where evaporation is in general higher.

4. Determining the Mathematical Form for Illustrating the Influence of Green Matter on Evaporation

According to lysimetric experiments (5, 6, 7, 8, 9), the function $[1 + f(Q)]$ can be presented as: $1 + \sqrt[3]{Q^2}$.

Hence the general formula for field evaporation considering the plant coverage is as follows:

$$V = V_0[1 + \beta \sqrt[3]{Q^2}], \tag{3}$$

in which:

Q — yield in q/ha harvested at the end of the period under study,
β — coefficient depending upon the kind of vegetation,
V_0 — field evaporation during this period at very small yields i.e. at $Q = 0$.

Let us compare this equation with the results of computations carried out on the above cited material by Preobrazenski. Figs. 2, 3, 4, exemplify—in graphical form—the interrelation between V and Q (curves defined by points). Assuming the shape of the curve according to formula 3, and carrying out the proper computations, it is possible to determine value V_0 and β for each of the curves drawn through a number of points, or in other words to reduce the graphical inter-relation to a mathematical form.

In this way type 3 formulae were obtained with concrete coefficients V^0 and β shown in Fig. 2, 3, 4 in the form of unbroken curves.

The relation $V/V_0 = 1 + \beta \sqrt[3]{Q^2}$ computed for the curves from Figs. 2, 3, 4 is presented in Figs. 6, 7, 8, which also show the results of lysimetric tests conducted by the author.

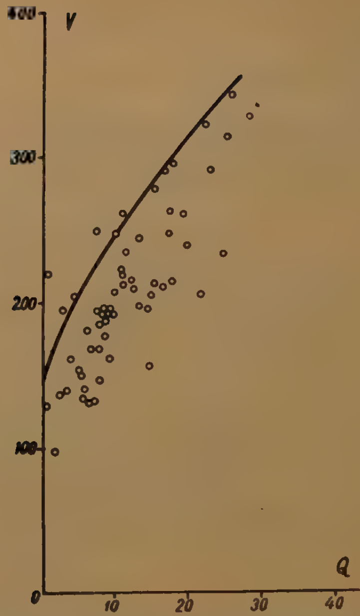


Fig. 5 — Water utilization (V in mm) and spring wheat grain yields (Q in q/ha) in the tschernozem zone of the Soviet Union according to Alpatiew.
The curve determines the relation obtained by Preobrazenski for Kazachstan-region.

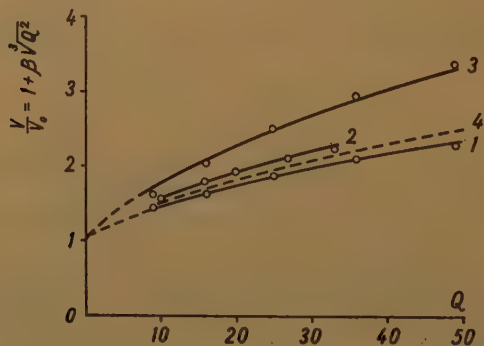


Fig. 6 — Interrelation between evaporation and yields of wheat
V — evaporation in mm of crop area
V_0 — evaporation in mm of uncovered area
Q — grain yield in q/ha
Curves 1-3 according to Preobrazenski in dry region of the Soviet Union;
Curve 4 — according to author's lisymetric's experiments in Poland
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management
4 — lisymetric observation on heavy alluvial soils with ground water level at 40-130 cm i.e. in conditions of medium moisture.

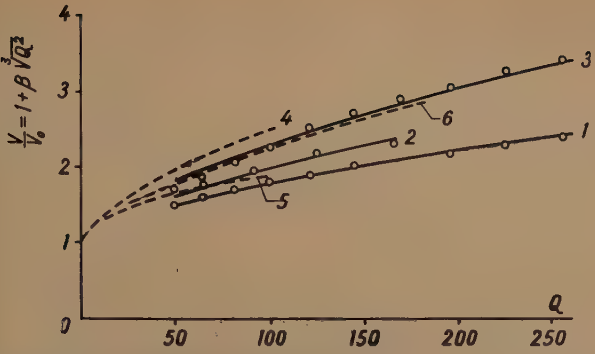


Fig. 7 — Interrelation between evaporation and yields of alfa-alfa and grasses
V — evaporation in mm of crop area
V_0 — evaporation in mm of uncovered area
Q — yield of hay in q/ha
Curves 1-3 according to Preobrazenski in dry region of the Soviet Union. Curves 4-6 for grass mixtures according to author's lisymetric experiments in Poland
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management
4 — lisymetric observation on heavy alluvial soils with ground water level at 40-130 cm i.e. in condition of medium moisture
5 — lisymetric observation on low peat lands, slightly humificated, with ground water level at 20-80 cm i.e. in conditions of high moisture
6 — lisymetric observation on low peat lands, with great content of calcium carbonate; water level at 15-90 cm i.e. conditions medium and high moisture.

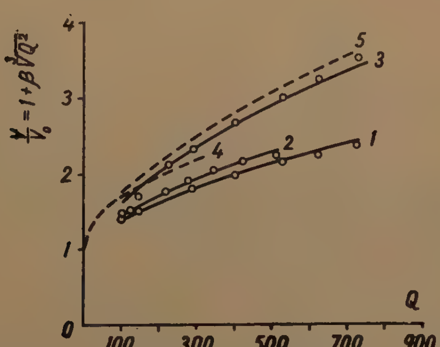


Fig. 8 — Interrelation between evaporation and yields of root crops
V — evaporation in mm of crop area
V_0 — evaporation in mm of uncovered area
Q — yields of roots in q/ha.
Curves 1-3 (sugar beets) according to Preobrazenski in dry region of the Soviet Union; Curves 4-5 according to author's lisymetric's experiments in Poland
1 — at excessively high irrigation ratio and low level of agriculture
2 — at medium level of agriculture and water management
3 — at high level of agriculture and proper water management
4 — lisymetric observation on potatoes on low peat lands with ground water level at 20-80 cm i.e. in conditions of high moisture
5 — lisymetric observation on sugar beets on heavy alluvial soils with ground water level at 40-130 cm i.e. in condition of medium moisture.

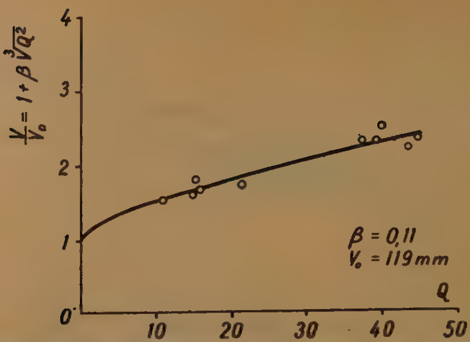


Fig. 9 — Interrelation between evaporation and yields of cotton (according to data by Ryzow).

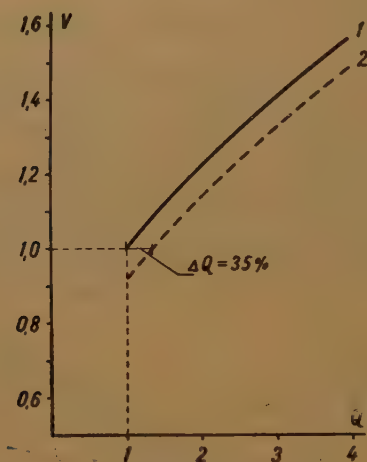


Fig. 10 — Evaporation increase as depending upon crop increases at medium initial level of yields and in medium conditions of evaporation.
1 — at unchanged agricultural conditions
2 — at improved agricultural conditions
ΔQ — Theoretical water reserves allow increasing yields by 35% without increasing evaporation outgo providing agricultural measures are improved.

In addition results of computations are given in Fig. 9, based on hydrological observations, but not of lysimeters, only from larger areas consisting of cotton fields according to material from the study by Ryzow ([13]).

By analyzing graphs 2-9, the following conclusions were reached:

1. The influence of crop yields on evaporation expressed by formula (3) based on hydrological measurements from lysimeters and in the field, is confirmed by investigations based on the energetic balance method. This is proved by sufficient coincidence of computed curves with points of observations.

2. The influence of plant matter on evapotranspiration is greater at a high level of agriculture, as V_0 representing unproductive evaporation, is here lower. At a low

level of agriculture or excessive irrigation, V_0 is higher, and the influence of yields on water outgo is therefore lower. It is obvious that total outgo is smaller in the first than in the second case.

3. Lysimetric data obtained by the author in Poland, and concerning the influence of yields on evaporation, are close to the values obtained through observations by means of the energetic method in a dry climate.

4. Formula 3 can be accepted as expressing evaporation increase in relation to crop yields.

It should be noted, however, that the form of the interrelation between evaporation and yield according to formula 3 obtained empirically, is not the only form. Depending upon the range of the limits of the experiment, the observed points could correspond for instance to $1 + \beta_2 \sqrt{Q}$, or even $1 + \beta_2 Q$.

Further considerations will be based, however, on the interrelation given in formula 3, as being in accordance with fairly numerous experimental material in a broad range of yields and evaporation.

5. The Relation of Evaporation at Increased Yields to Initial Evaporation

Direct determination of evaporation from formula 3 necessitates determining V_0 and β for various conditions. In some cases these coefficients are known from experiments. Thus for example we possess data relating to: evaporation of meadows on low peats (5), on heavy deep alluvial soils (6), wheat on alluvial soils (7), evaporation of meadows on bog peatlands (8), and sugar beets on alluvial soils (9).

If however evaporation is known at only given yields, then evaporation can be determined in general for increased yields as follows.

Assuming that in given conditions evaporation on a certain area is defined by equation 3:

$$V = V_0 (1 + \beta_1 \sqrt[3]{Q^2}) \tag{4}$$

it is evident that in different conditions (for example after meliorations) at n-greater crop yields, evaporation from this same area will be:

$$V_n = V_0' (1 + \beta_2 \sqrt[3]{Q^2} \cdot \sqrt[3]{n^2}) \tag{5}$$

The relation V_n/V is:

$$\frac{V_n}{V} = \frac{V_0' (1 + \beta_2 \sqrt[3]{Q^2} \cdot \sqrt[3]{n^2})}{V} \tag{6}$$

From equation 4 Q is determined and substituted in equation 6:

$$\sqrt[3]{Q^2} = \frac{1}{\beta_1} \left(\frac{V}{V^0} - 1 \right)$$

$$\frac{V_n}{V} = \frac{V_0' \left[[1 + \frac{\beta_2}{\beta_1} \left(\frac{V}{V_0} - 1 \right) \sqrt[3]{n^2} \right]}{V}$$

The following is obtained after transforming:

$$\frac{V_n}{V} = \frac{V_0'}{V_0}\left[\frac{\beta_2}{\beta_1}\sqrt[3]{n^2} - \frac{V_0}{V}\left(\frac{\beta_2}{\beta_1}\sqrt[3]{n^2} - 1\right)\right] \tag{7}$$

This formula indicates changes taking place in evaporation at yield increases, and at simultaneous changes of external conditions.

If conditions (for example water, soil, climatic or agricultural) do not change with yield increases, then $V_0 = V_0'$ and $\beta_2 = \beta_1$, and equation 7 changes as follows:

$$\frac{V_n}{V} = \sqrt[3]{n^2} - \frac{V_0}{V}(\sqrt[3]{n^2} - 1) \tag{8}$$

And lastly in a special case, if in unchanged conditions unproductive evaporation V_0 is very small in comparison to V, then:

$$\frac{V_n}{V} = \sqrt[3]{n^2} \tag{9}$$

Use of the relation V_n/V according to equations 7-9 is founded by the fact that it is frequently easier to evaluate the relations:

$$\frac{V_0'}{V}, \ \frac{V_0}{V} \text{ and } \frac{\beta_2}{\beta_1}$$

than their absolute values.

It should be noted that a somewhat different relation V_n/V is given a former publication (2), namely:

$$\frac{V_n}{V} = \sqrt{n} - \frac{V_0}{V}(\sqrt{n} - 1) \tag{10}$$

This formula, simplified and valid for unchanged external conditions, was based on less extensive material and on assuming a different form of curve, illustrating the connection between evaporation and yields, but giving values sufficiently close to results obtained with the analogous formula 8 enclosed in this paper.

It should be additionally noted that Czerkasow [3] gives the following interrelation:

$$\gamma_n = \frac{\gamma}{\sqrt{n}}, \text{ or } \frac{V_n}{V} = \sqrt{}$$

accepting $V = \gamma \cdot Q$ and $V_n = \gamma_n \cdot Q \cdot n$, then the above can be sufficiently accurate in certain ranges for V and Q.

Inasmuch as the formulae (2-9) given herein have a more general character than formulae heretofore used and conform fairly well with results obtained by means of the energetic method, they will therefore be used for further considerations.

6. Numeral Indices for Evaporation Changes

A. An estimation of values for evaporation changes will be begun from the case corresponding to formula 9. This will constitute a fairly rare case, as although the

relation V_0/V lies within the range 0 and 1, practically it can become zero only in exceptional cases, for example if evaporation from the soil surface is totally checked. Experiments show that the relation V_0/V is equal to at least several tenths, and according to data from Figs. 6-8, even at a very high V, the relation V_0/V does not fall below 0.25.

Therefore assuming $V_0/V = 0$, we obtain V_n/V as the theoretically maximum possible limit of evaporation increase resulting from increased yields. However even in this unfavorable case, evaporation increases considerably slower than yields, as illustrated in Table 1 (Table 1).

TABLE 1

Evaporation Changes with Crop Increase Taking Place According to Formula 9

Crop increase n	Relation of increased to initial evaporation V_n/V
1	1
1.25	1.16
1.50	1.31
1.75	1.45
2.00	1.59
3.00	2.08
4.00	2.52
5.00	2.92

TABLE 2

Value for V_0/V (i.e. evaporation at minimum plant cover to evaporation from an area covered with cultivated vegetation) computed according to data published by Preobrazenski for dry irrigated areas

Level of agriculture	Outgo of water	Initial level of yields accepted for the computations		
		Low cereals 10 q/ha sugar beets 100 q/ha hay 15 q/ha	Medium cereals 15 q/ha sugar beets 175 q/ha hay 25 q/ha	High cereals 25 q/ha sugar beets 300 q/ha hay 40 q/ha
1. Low	high	0.74	0.68	0.60
2. Medium	medium	0.70	0.63	0.53
3. High	low	0.63	0.55	0.47

B. Let us now consider evaporation changes taking place according to formula 8 i.e. at unchanged external conditions.

It is clear that only relative unchangeability can here be taken into consideration, as without doubt every yield increase exerts an influence on soil microclimate.

As mentioned the ratio V_0/V ranges from 0 to 1. In order to define it more accurately, at least three categories of crop yields and 3 categories of external conditions influencing evaporation must be analyzed. An analysis of material available from Figs. 2-4 rendered it possible to elaborate Table 2, which presents the value of the ratio V_0/V in various conditions. (Table 2).

Table 3 presents the values of V_0/V obtained from local lysimetric experiments. As can be noted these values are close to those presented in Table 2 for medium utilization of water. (Table 3).

TABLE 3

Value for V_0/V according to author's lysimeter experiments

Vegetation and soil conditions	Initial level of yields: Low	Medium	High
Grasses on heavy alluvial soils	0.703	0.626	0.550
Grasses on low peat lands	0.738	0.705	0.633
Potatoes on low peat lands	0.623	0.567	0.502
Wheat on alluvial soils	0.692	0.632	0.550
average	0.69	0.63	0.56

TABLE 4

Values for V_n/V (i.e. increased evaporation to initial evaporation) according to formula 8, and coefficients from Table 2

Initial level of yields	Low			Medium			High		
	Level of agriculture and water economy								
Yield increase n	Low	Medium	High	Low	Medium	High	Low	Medium	High
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.25	1.04	1.05	1.06	1.05	1.06	1.07	1.06	1.07	1.08
1.50	1.08	1.09	1.12	1.10	1.12	1.14	1.12	1.15	1.16
1.75	1.12	1.13	1.17	1.14	1.17	1.20	1.18	1.21	1.24
2.00	1.15	1.18	1.22	1.19	1.22	1.26	1.24	1.28	1.31
3.00	1.28	1.32	1.40	1.34	1.40	1.50	1.43	1.51	1.57
4.00	1.40	1.46	1.56	1.49	1.56	1.68	1.61	1.71	1.81
5.00	1.50	1.58	1.71	1.61	1.71	1.86	1.77	1.90	2.02

Table 4 was compiled on the basis of Table 2, and illustrated the increase of evaporation under the influence of crop increases in unchanging external conditions. (Table 4).

If therefore $V_0/V = 0$, then evaporation increases considerable more slowly than in accordance with Table 2, reaching for instance at a 5-fold increase of yields only a 1.5 to 2 fold increase. However the values in Table 4 should be looked upon as a certain upper limit of evaporation increase. Changes in agricultural methods and the water economy can still result in a decline of obtained specific data.

C. Lastly it is necessary to analyze the case, in which the level of agriculture and water economy increase parallel to yield increases, thereby assuring economical water utilization; in this case phenomena take place according to formula 7.

In order to determine the value V_0'/V_0 and β_2/β_1, included in this formula, advantage was taken in the first place of material published by Preobrazenski. It should be emphasized however that this data is based on conditions differing considerably from Polish conditions, and relate to dry irrigated regions where the possibilities of economic water utilization are relatively high, depending upon the agricultural measures applied. To a certain extent the equalizing factor in Polish conditions is rainfall, which partially evaporates from the surface of plants and exerts an equalizing influence on the water content of upper soil layers deciding on unproductional evaporation.

Results of computations are compiled in Table 5. (Table 5).

TABLE 5

Values for V'_0/V_0 and β_2/β_1 according to material by Preobrazenski for irrigated areas

Changes in the level of agriculture influencing more economical utilization of water	$\frac{V'_0}{V_0}$	$\frac{\beta_2}{\beta_1}$	Remarks
Increasing the level of agriculture and water economy from low to medium	0.82	1.23	Changes resulting from cultivation and fertilization measures, from introducing furrow irrigation instead of flooding and with smaller and more frequent applications of water ratio
Increasing the level of agriculture and water economy from medium to high	0.73	1.38	

From our experiments, the following values for the ratio V_0'/V_0 were obtained:

1. Draining a low peatland from 20 cm to 40 cm — 0.851
Draining heavy alluvial soils from 40 cm to 80 cm — 0.937
Shallow plowing of stubble on alluvial soils — 0.703
Draining of shallow alluvial soils from 50 cm to 75 cm — 0.880

2. Draining low peatland from 40 cm to 80 cm — 0.737
Draining heavy alluvial soils from 80 cm to 130 cm — 0.876
Shallow plowing of stubble on alluvial soils — 0.703
Draining of shallow alluvial soils from 75 cm to 130 cm — 0.768

On an average application of melioration measures which assure only a medium decrease of water outgo, gives $V_0'/V_0 = 0.84$, more intensive measures give $V_0'/V_0 = 0.77$. Hence these values are close to the figures cited in Table 5, although somewhat higher or in other wo.ds indicating smaller possibilities of economizing on water.

As concerns the value β_2/β_1, less direct data is available; it can be assumed however that such figures would not differ to any great extent from those given in Table 5. Further proof can be found in the fact that the ratio β_2/β_1, computed from the dispersion of points observed according to lysimeter experiments ranges from 1.3 to 1.5.

By accepting V_0/V according to Table 3, and V_0'/V_0 and β_2/β_1 according to Table 5, Table 6 was compiled. (Table 6).

TABLE 6

Changes in relation of evaporation V_n/V_0 with yield increases and simultaneous raising of levels of agriculture and water management assuring economical utilization of water (according to data by Preobrazenski for irrigated fields in dry areas)

Initial level of yields	Low		Medium		High	
	Changes of level of agriculture and water management					
Yield increases *n*	from low to medium	from medium to high	from low to medium	from medium to high	from low to medium	from medium to high
1.	0.87	0.81	0.88	0.83	0.88	0.84
1.25	0.91	0.87	0.93	0.89	0.94	0.92
1.50	0.95	0.90	0.96	0.94	1.01	0.99
1.75	0.98	0.95	1.02	1.00	1.06	1.05
2.00	1.02	0.99	1.07	1.05	1.12	1.12
3.00	1.15	1.14	1.22	1.23	1.31	1.35
4.00	1.26	1.27	1.36	1.39	1.49	1.56
5.00	1.37	1.39	1.47	1.54	1.65	1.75

In the conditions under discussion (dry regions), and at improved agricultural measures and water management, increased evaporation would be evoked only after a 1.5-2 fold crop yield increase; water reserves possible to attain would then reach 10-20% of the initial state.

As already mentioned, economy in water utilization in Polish conditions would be not as great as those resulting from Table 6. Poland possesses a good deal of land partially drained, and such measures as shallow post-harvest plowing are also fairly universal.

It is therefore proper to treat the values given in Tables 5 and 6 as tentative maximum and minimum limite, which include evaporation increase.

Table 4 gives the upper maximum limit of evaporation increase, Table 6 the lower limit i.e. the minimum expected increase.

Due to the lack of precise data it can be assumed, that probable evaporation changes resulting in Poland from yield increases in conditions of changed, improved agricultural methods would appear as averages of Tables 4 and 6.

On this basis collective Table 7 was computed, illustra ing evaporation increases possible in Polish conditions. Some of the data from Table 7 is graphically presented in Fig 10. (Table 7).

In conditions in which there is no assurance of economizing on water, evaporation increase indices should be used according to p. a; there where taking advantage of reserves is certain, p. b is more appropriate.

It should be additionally noted that tentative values for increased evaporation according to Table 7 relate to greater areas analyzed as a whole. In particular meliorated objects, applicated net water ratio resulting from increased outgo, should be the more precisely and carefully determined the smaller the given object.

The greater the areas analyzed, the more proper it is to allow for mutual compensation of water in each of the parts of such an area, due to which the results of changes in the circulation of water should be smaller in reference to the last point of the basin than in each of its parts.

7. Comparison of Indices in Changes of Evaporation with Observations on Balances in Nature on Larger Areas, and Final Conclusions

Dubrowin and Roginski [4] elaborated water balances for the Notec River Basin for the period 1863-1937 distinguishing three periods which differ distinctly in respect to the volume of crop production. This work presents precipitation and runoff for specific periods according to hydrological data, and also computations by the authors of field evaporation. Furthermore the amount of vegetable matter produced was determined on the basis of agricultural statistics. Results of these studies are given in Table 8.

TABLE 8

Relative value of yields and evaporation in the Notec River Valley

Basin	Area in sq. km.	Period	Years	Relative value of agricultural production yields	Relative value of field evaporation According to Dubrowin and Roginski	According to Ostromecki
Notec, central flow	6365	I	1863-1892	1.00	1.00	1.00
		III	1926-1937	2.03	1.11	1.09
		II	1902-1910	2.43	1.21	1.15
Notec, upper flow	2187	III	1926-1937	1.00	1.00	1.00
		II	1902-1910	1.19	1.06	1.05

It can be assumed that figures presenting evaporation increase obtained by the method presented herein, and data from direct computation are sufficiently close.

TABLE

Tentative value of field
(i.e. evaporation at yields increased
for various

Initial conditions	Conditions after crop increase	Initial: Low, ranging: cereals 8-12 q/ha, sugar beets 80-120 q/ha, potatoes 60 60-90 », meadow hay 10-20 »						
		Crop						
		1	1.25	1.5	1.75	2	3	4
Conditions favorable for high evaporation. Meadows wet, without drainage on peat lands or bogs. Primitive system of irrigation, for example flooding without drainage. Fields without drainage, low and wet, without tree stands. Low level of agriculture, high unproductive evaporation due to the lack of deep plowing, cultivations, etc. High possibilities of economizing on water. Soils without structure, low fertility	*a*) without changing	1.00	1.04	1.08	1.12	1.15	1.28	1.40
	b) conditions subject to change to medium level consisting of improving agriculture and introducing fairly intensive meliorations	0.94	0.98	1.02	1.05	1.09	1.22	1.33
Medium evaporation. Meadows fairly wet, meliorated but irrigation arrangements mediocre (usually flooding or sub irrigation), medium drainage arrangements on peat or alluvial soils. Field without drainage, periodically wet, medium fertility and soil structure. Agricultural measures sufficient but not high; reserves can be obtained in economizing on water	*a*) without changing	1.0	1.05	1.09	1.13	1.18	1.32	1.46
	b) conditions subject to change to high productivity, agricultural measures improved. Introduction of intensive meliorations for example instead of flooding sprinkle irrigation	0.91	0.96	1.00	1.04	1.09	1.23	1.37

7
evaporation changes V_n/V
n-times in relation to initial evaporation)
categories of fields

yields

Medium, ranging: cereals 12-18 q/ha sugar beets 120-230 q/ha potatoes 90-150 » meadow hay 20-30 »						Medium, high, ranging: cereals 18-32 q/ha sugar beets 230-270 q/ha potatoes 150-250 » meadow hay 30-50 »				
increase										
1	1.25	1.5	1.75	2	3	1	1.25	1.5	1.75	2
1.00	1.05	1.10	1.14	1.19	1.34	1.00	1.06	1.12	1.18	1.24
0.94	0.99	1.04	1.08	1.13	1.28	0.94	1.00	1.07	1.12	1.18
1.00	1.06	1.12	1.17	1.22	1.40	1.00	1.07	1.15	1.21	1.28
0.92	0.98	1.03	1.09	1.14	1.32	0.92	1.00	1.07	1.13	1.20

TABLE

Tentative value of field
(i.e. evaporation at yields increased
for variou

Initial conditions	Conditions after crop increase	Initial Low, ranging: cereals 8-12 q/ha sugar beets 80-120 q/ha potatoes 60 60-90 » meadow hay 10-20 » Crop 1	1.25	1.5	1.75	2	3	4
Low evaporation especially unproductive. Meadows and grassland unirrigated. Drained and simultaneously irrigated meadows with possibility of great economy on water on alluvial soils. Fields drained, high soil structure and fertility. Areas covered with trees, vegetable gardens watered. High level of agriculture, low reserves in future economizing on water	*a*) conditions in general without greater changes. Resp. on unirrigated areas introduction of irrigation	1.00	1.06	1.12	1.17	1.22	1.40	1.56

7 *(continued)*
evaporation changes V_n/V
n-times in relation to initial evaporation)
scategories of fields

yields										
Medium, ranging: cereals 12-18 q/ha; sugar beets 120-230 q/ha; potatoes 90-150 »; meadow hay 20-30 »						Medium, high, ranging: cereals 18-32 q/ha; sugar beets 230-270 q/ha; potatoes 150-250 »; meadow hay 30-50 »				
increase										
1	1.25	1.5	1.75	2	3	1	1.25	1.5	1.75	2
1.00	1.07	1.14	1.20	1.26	1.50	1.00	1.08	1.16	1.24	1.31

On this basis it is possible to apply the method given to general computations concerning future requirements and utilization of water by agriculture in Poland.

Preliminary computations indicate that as agricultural production increases, evaporation will increase by around 30 mm annually; in relation to present evaporation which is around 450 mm, this constitutes 7%. Part of this increase will without doubt be covered by decreasing the flow of rivers during the summer season. Hence the future problem for meliorations will be confined to storage of water for agricultural needs.

BIBLIOGRAPHY

(1) Alpatiew : Wlagooborot kulturnych rastenij (The moisture turnover in crops) Leningrad 1954.

(2) Bac S., Ostromecki J. : Melioracje rolne w gospodarce wodnej Polski (Agricultural meliorations in water management in Poland). « *Gospodarka Wodna* » Warszawa 1948.

(3) Czerkasow A. A. : Selskochoziajstwiennyje melioracji i wodosnabzenije (Agricultural meliorations and the water supply). Moskwa 1952.

(4) Dubrowin T., Roginski S. : Oddzialywanie rolnictwa i lesnictwa na bilans wodny zlewni Noteci powyzej ujscia Gwdy (The influence of agriculture and forestry on the water balance in the Notec river basin in its central flow) *Prace i Studia Komitetu Gospodarki Wodnej PAN*. Warszawa 1956.

(5) Ostromecki J. : Projektowanie rownowagi bilansu wodnego dla meliorowanych zlewni bagiennych (Projecting of a water balance for the meliorated boggy basins). *Wiadomosci Sluzby Hydrologicznej i Meteorologicznej*. Warszawa 1947.

(6) Ostromecki J. : Potrzeby wodne i parowanie lak na madach glebokich (The water needs and the evaporation of meadows on deep alluvial soils). «*Gospodarka Wodna*». Warszawa 1951 z. 1-2.

(7) Ostromecki J. : Parowanie terenowe pszenicy na madach (The field evaporation of wheat on alluvial soils). «*Gospodarka Wodna*» Warszawa 1956 z. 6.

(8) Ostromecki J. : Potrzeby wodne lak na namulonych torfach weglanowych (The water needs on carbonated peat lands) in print Roczniki Nauk Rolniczych. Warszawa.

(9) Ostromecki J. : Parowanie terenowe burakow cukrowych na madach (The field evaporation of sugar beets on alluvial soils) in print Roczniki Nauk Rolniczych Warszawa.

(10) Preobrazenski T. N. : Metod opredielenija isparenija na oroszajemych zemliach (Method of determination of evaporation on irrigated lands). «*Gidrotiechnika i Melioracija*» Moskwa. 1951 z.l.

(11) Preobrazenski T. N. : Wodopotreblenije jarowoj pszenicy pri oroszenii w stiepnych rajonach SSSR (The use of water by spring wheat on irrigated steppe areas of the Soviet Union). «*Gidrotiechnika i Melioracija*» Moskwa. 1951 z. 10.

(12) Preobrazenski T. N. : Wieliczina summarnogo wodopotreblenija kulturami pri oroszenii (The volume of total use of water by irrigated crops) «*Trudy WNISGM*» t. XXVII-XXVII. Moskwa. 1952.

(13) Ryzow : Naprawlennaja peredielka prirody poczw w uslowijach oroszajemogo zemledielija (Directed change of soil nature in the conditions of irrigation agricultre) «*Poczwowiedienie*» Moskwa. 1949.

CONSOMMATION D'EAU PAR QUELQUES PLANTES AGRICOLES AUX CONDITIONS DES CHAMPS

STANISLAW BAC
Pologne

De longues recherches, effectuées par l'Auteur à l'aide des lysimètres et dans les champs agricoles, pendant plus de dix ans, lui ont permis de constater que le rendement des plantes agricoles en Pologne dépend non pas du volume des précipitations atmosphériques de l'année ou de la période de végétation, mais uniquement de la disposition de celles-là dans le temps.

Pour établir, d'une façon plus précise, la consumption de l'eau par les plantes agricoles (évaporation + transpiration des plantes + écoulement), l'Auteur a organisé un Champ Permanent, à Czechnica près de Wroclaw (N 51° 2' — E 17° 9').

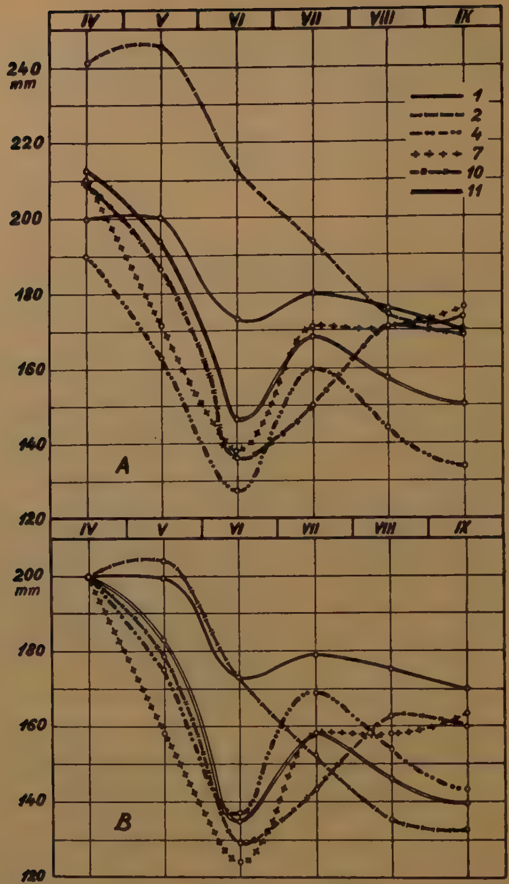
La rotation, la culture, le fumier et les variétés des plantes constituaient les *facteurs stables* du Champs Permanent, tandis que le parcours des agents atmosphériques qui influent sur l'humidité du sol a été son *unique facteur instable.*

Les observations météorologiques et les recherches sur l'humidité du sol (jusqu'à 100 cm de profondeur), poursuivies au cours de six ans, ont prouvé que chaque espèce de plante de la rotation trouve une quantité différente de l'humidité dans le sol au début de la période de végétation. Cette quantité dépend des cultures actuelles et précédentes. La quantité d'eau dans les champs particuliers peut varier jusqu'à 500 m³/ha, et chaque plante puise l'humidité du sol à sa propre façon.

TABLEAU I

Humidité du sol initiale $(W)_p$, *minimum* (W_{min}) *et finale* (W_k) *et valeurs de la diminution d'humidité dans une couche de sol de 100 cm avec cultures (champ expérimental à Czechnica, 1950-1955)*

N°	Culture	Humidité du sol en mm: W_p 1.IV	W_{min}	Mois	W_k 30.IX	W_p—W_{min}	W_p—W_k	Culture antérieure
1	Sans végétation	198,2	175,6	IX	169,8	22,6	28,4	Sans végétation
2	Betterave à sucre	244,0	174,4	IX	184,0	69,6	60,0	Blé d'hiver
3	Pommes de terre	244,6	171,4	IX	172,0	73,2	72,6	Seigle d'hiver
4	Gazon	214,7	138,3	VI	146,7	76,4	68,0	Gazon
5	Trèfle	215,1	135,8	VI	140,0	79,3	75,1	Orge d'hiver
6	Navette d'hiver	228,0	138,9	VI	185,0	89,1	43,0	Trèfle
7	Seigle d'hiver	225,5	143,4	VI	186,8	82,1	38,7	Orge d'hiver
8	Orge d'hiver	233,8	146,1	VI	191.6	87,7	42,2	Trèfle
9	Blé d'hiver	224,3	146,0	VI	186,5	78,2	37,7	Navette d'hiver
10	Blé de printemps	209,8	146,1	VI	193,3	63,7	16,5	Pomme de terre
11	Orge de printemps avec trèfle	216,7	152,3	VI	170,0	64,4	46,7	Betteraves à sucre
12	Avoine avec trèfle	211,9	159,5	VI	162,8	62,4	49,1	Blé de printemps
	Médiocre	222,2	151,5		174,0	70,7	48,2	



Przebieg średniej wilgoci gleby pod poszczególnymi uprawami
A-rzeczywisty, B-zestawiony do wspólnej wilgoci początk.

1 —— pole bez roślin *7 +++++ żyto ozime*
2 — — buraki cukrowe *10 —•—• pszenica jara*
4 —·· trawnik *11 ═══ jęczmień jary z koniczyną*

Fig. 1 — Le parcours de l'humidité moyenne du sol, relativement aux différentes cultures.
A — réel, B — en relation avec l'humidité générale du début.
1. Sans plantes, 2. La betterave sucrière, 4. La pelouse, 7. Le seigle d'hiver 10. Le froment printanier, 11. L'orge printanier avec le trèfle.

De la table 1, on peut conclure :

a) Au printemps, une humidité maximum possèdent les champs cultivés mécaniquement, avec engrais organique, préparés pour la culture des plantes potagères (env. 245 mm); une humidité minimum possèdent les champs sans végétation (198 mm). La différence d'humidité entre les champs cultivés avant l'hiver et les champs sans végétation, en des conditions climatiques de Pologne, sur sols légers, atteint 50 mm.

b) Le champ sans végétation montre la moindre différence entre l'humidité maximum et l'humidité minimum (28 mm); les champs après les blés d'hiver montrent des différences maxima (78-89 mm).

c) Les minima d'humidité ont lieu en septembre pour les champs sans végétation, en juin — pour toutes les cultures.

Pour établir le bilan d'eau d'un champ agricole qui n'occupe qu'une partie minime de la surface du bassin dont on prend l'écoulement en masse, l'Auteur a formulé la suivante équation du bilan pour un mois :

$$W_p + P = S + W_{sr}$$

ou : W_p — correspond à l'humidité du sol au début du mois
P — correspond au volume de précipitation atmosphériques du mois
S — correspond à la consumption de l'eau du champ agricole (évaporation du terrain + écoulement du champ)
W_{sr} — correspond à l'humidité moyenne du sol au cours d'un mois, établie à l'aide de 4 à 5 mesures.

La consumption de l'eau de champs équivaut donc à :

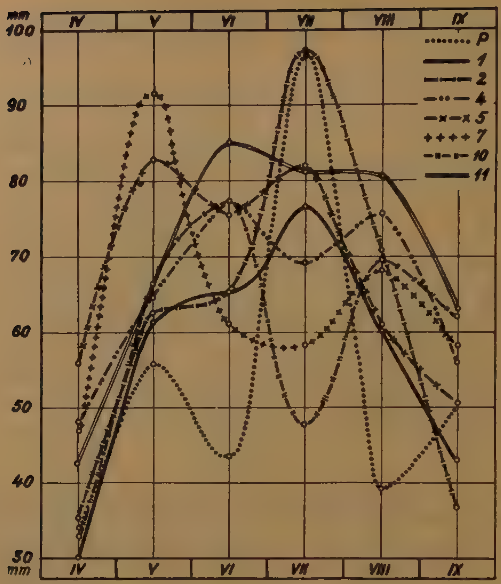
$$S = W_p + P - W_{sr}$$

La consumption de l'eau de champs, établie d'après cette formulier, a montré de différents parcours et des quantités différentes de l'eau consumée dans les champs plantés de 11 plantes agricoles et dans un champ sans végétation.

TABLEAU II

La moyenne mensuelle de l'humidité du sol (W_{sr}) en mm des champs aux cultures différentes — dans le Champ Permanent de Czechnica — étés de 1950 à 1955

Nº	La plante agricole	La moyenne mensuelle de l'humidité de sol (W_{sr}) en mm VI	V	VI	VII	VIII	IX	moyenne IV-IX
1	Sans plantes	203,7	206,6	180,6	189,9	187,9	175,6	190,7
2	La betterave sucrière	242,2	244,8	218,6	201,2	183,8	174,4	210,8
3	La pomme de terre	240,1	241,6	214,8	203,3	182,2	171,4	208,9
4	La pelouse	196,8	173,7	138,3	161,0	159,3	149,3	161,4
5	Le trèfle	198,6	172,1	135,8	159,1	149,7	141,7	159,4
6	La navette d'hiver	206,9	166,5	138,9	175,6	180,6	183,7	175,4
7	Le seigle d'hiver	219,9	195,4	143,4	171,7	174,0	181,3	180,9
8	L'orge d'hiver	218,5	183,0	146,1	176,9	182,4	179,9	181,1
9	Le froment d'hiver	217,5	191,0	146,0	173,2	175,8	176,5	180,0
10	Le froment printanier	214,0	194,1	146,1	176,1	181,2	174,3	181,0
11	L'orge printanier avec la trèfle	213,8	198,3	152,3	170,6	166,4	161,3	177,1
12	L'avoine avec la trèfle	206,5	197,1	149,5	173,1	171,8	166,7	177,4
(W_{sr})	La moyenne mensuelle de l'humidité	214,9	197,0	159,2	177,6	173,7	169,7	182,0



Przebieg średniego polowego zużycia wodnego (S) i opadów (P) w półroczu letnim

P opad — *5 koniczyna*
1 pole bez roślin — *7 żyto ozime*
2 buraki cukrowe — *10 pszenica jara*
4 trawnik — *11 jęczmień jary z koniczyną*

Fig. 2 — Le parcours de la consumption moyenne de l'eau (S) et des précipitations atmosphériques (P) dans le semestre d'été.
P. La précipitation, 1. Sans plantes, 2. La betterave sucrière, 4. La pelouse, 5. Le trèfle, 7. Le seigle d'hiver, 10. Le froment printanier, 11. L'orge printanier avec le trèfle.

De la table II et fig. 2 on peut conclure :

a) Chacune des cultures étudiées, et même le champ sans végétation, montrent une consommation hydrique moyenne supérieure au total des précipitations d'été.

b) Une consommation hydrique la plus grande montre le trèfle avec plante protectrice (402 mm pendant le premier été de végétation et 395 mm — pendant le deuxième) en donnant un déficit d'eau de 70 à 90 mm. Les plantes potagères qui croissent pendant tout l'été, consomment 375 mm d'eau en moyenne, donnant un déficit de 50 mm. Le total de la consommation hydrique depuis le 1.IV jusqu'à la fin de juin monte à 200 mm; vu que la lame des précipitations dans ces mois est de 134 mm en moyenne, le déficit doit être suppléé par l'humidité du sol qui en juin diminue avec grande vitesse. Le champ sans végétation consomme le moins d'eau et le total du déficit n'y monte qu'à 9 mm.

c) Une consommation hydrique mensuelle maximum montrent les cultures suivantes :

en mai — le seigle d'hiver, la navette d'hiver, le trèfle la deuxième année de sa végétation, l'orge d'hiver et le blé d'hiver;

en juin — l'orge et l'avoine avec trèfle, le blé de printemps et le gazon;

en juillet — la betterave à sucre et le sol sans végétation.

Le volume de la consumption de l'eau pendant la période de la végétation (IV-IX) surpasse en moyenne le volume des précipitations atmosphériques de la même période du temps de 50 mm environ.

Si l'on soustrait le volume des précipitations atmosphériques pour chaque mois (P) de la consumption de l'eau des champs (S), on obtient les déficits et les excédents de précipitations.

L'excédent moyen de précipitations atmosphériques, pendant les six mois d'été (pour le climat de la Pologne), n'existe pour toutes les plantes qu'au mois de juillet. D'autres mois présentent des déficits.

TABLEAU III

La moyenne de déficits (—) *et d'excédents* (+) *de précipitations atmosphériques* (P) *relativement à la consumption de l'eau* (S) *des plantes agricoles dans le Champ Permanent à Czechnica — étés de 1950 à 1955*

N°	La plante agricole	La moyenne de déficits et d'excédents précipitations en mm						somme
		IV	V	VI	VII	VIII	IX	IV-IX
1	Sans plantes	+ 5,5	+ 4,1	+21,7	+22,4	—14,9	+ 3,1	— 9,7
2	La betterave sucrière	— 1,8	— 7,9	—21,1	+ 2,9	—25,8	+ 4,5	—49,2
3	La pomme de terre	— 4,5	—11,7	—25,8	+10,8	—19,5	— 4,8	—55,5
4	La pelouse	—17,9	—32,1	—25,3	+27,1	—20,6	— 4,2	—73,0
5	Le trêfle	—16,4	—20,5	—35,4	+23,2	—18,0	— 2,1	—69,2
6	La navette d'hiver	—21,0	—25,0	—16,9	+35,0	—15,7	— 9,9	—53,5
7	Le seigle d'hiver	— 5,6	—15,5	—16,2	+35,5	—24,9	— 7,5	—34,2
8	L'orge d'hiver	—15,3	—20,8	—18,4	+38,2	—15,1	— 9,3	—40,7
9	Le froment d'hiver	— 6,9	—19,0	—25,4	+30,5	—24,8	—13,2	—58,8
10	Le froment printanier	+ 4,2	—10,3	—33,7	+49,3	—24,4	—21,4	—36,3
11	L'orge printanier avec la trêfle	— 2,9	— 9,5	—38,9	+18,7	—30,0	— 8,4	—71,0
12	L'avoine avec la trêfle	— 5,4	— 9,9	—30,8	+35,0	—23,7	— 9,3	—44,1
	La moyenne S — P	— 7,3	—15,5	—28,5	+27,4	—21,4	— 6,9	—49,6

En général on peut constater, d'après le volume de récoltes obtenues en six années, que la récolte dépend d'une quantité satisfaisante de précipitations atmosphériques et d'humidité du sol des champs agricoles au cours du mois exigeant le maximum de consumption de l'eau agricole par la plante donnée.

En comparant la corrélation entre la consumption de l'eau agricole (S) et le volume des précipitations atmosphériques (P) du mois — pour chaque mois en particulier — nous obtenons le coefficient de la consumption de l'eau par les plantes :

$$d = \frac{S}{P}$$

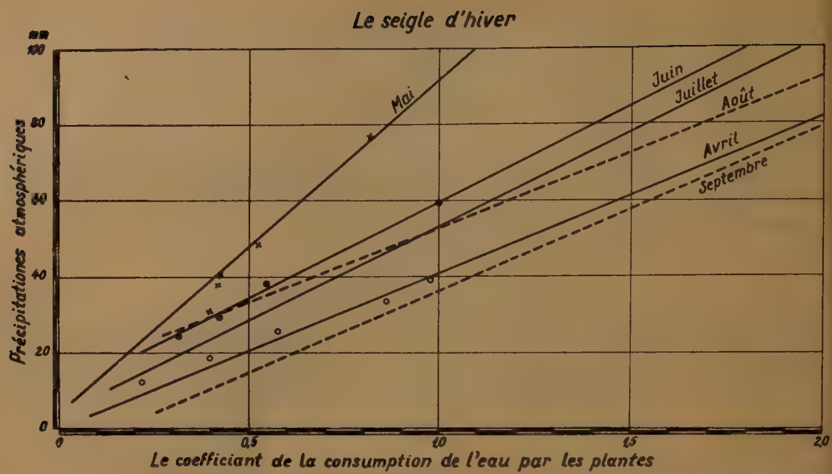


Fig. 3

D'après le coefficient *d* et le volume de précipitations dans les mois du semestre d'été — on a dessiné des diagrammes pour chaque espèce de plantes et pour chaque mois. C'est à l'aide de ces diagrammes qu'on peut établir la consumption de l'eau par les plantes dans les champs agricoles des autres bassins autant le climat et le sol analogues.

ON THE INFLUENCE OF THE VEGETATION OF HIGHLY PRODUCTIVE PEAT LANDS ON THE WATER BALANCE
ÜBER DEN EINFLUSS DER VEGETATION LEISTUNGSFÄHIGEN HOCHMOORGRÜNLANDES AUF DEN WASSERHAUSHALT

W. BADEN & R. EGGELSMANN (*)
Aus der Staatl. Moor-Versuchsstation in Bremen

Résumé

On a observé pendant sept ans les pluies, l'humidité du sol, les variations du niveau de la nappe d'eau souterraine, l'écoulement de l'eau, la température du sol, l'évaporation et le degré d'humidité de l'air sur un marais-vert cultivé (vieux 40 ans) et sur un marais inculte drainé sans tuyaux, en la Station d'essai Königsmoor.

Pour la croissance les mouvements de la nappe d'eau souterraine ont moins d'importance que la température et une mise en valeur intensive. En été le marais-vert à forte densité de plantation évapore plus d'eau que les surfaces incultes couvertes de mousse et de bruyère, il a le degré d'humidité de l'air plus grand — encore à deux mètres au — dessus du sol et la température de la couche d'air proche du sol plus régulière Grâce à l'évaporation plus fo rte et à l'intervalle poreux plus grand qui permet une plus grande absorption d'eau, le débit de l'eau qui écoule du terrain cultivé est plus régulier et en total plus faible. Les débits les plus forts apparaissent donc non pas sous les marais cultivés, mais sous les marais en friche.

L'influence de marais cultivé sur le climat des régions environnantes ne peut-être que favorable.

Einleitung

Über den Einfluss der Landeskultur und der Vegetation auf den Wasserhaushalt der Moore sind die Meinungen geteilt.

Als Beitrag zur Klärung dieser Frage werden seit 1951 im Königsmoor, Kreis Harburg-Land, auf kleineren Beispielsflächen hydrologische Untersuchungen vorgenommen. Sie sind von der Staatl. Moor-Versuchsstation Bremen in Zusammenarbeit mit dem Kuratorium für Kulturbauwesen in Westdeutschland — Unterausschuss Moor und Wasser — eingeleitet.

Für eine 40 Jahre alte Deutsche Hochmoorkultur und eine in unmittelbarer Nähe gelegene unkultivierte Hochmoorfläche (Grösse rd. 6 ha) werden tägliche Niederschlags-, Abfluss-, Verdunstungs- und Grundwassermessungen sowie mehrjährig Bodenfeuchtebestimmungen und zeitweilig Klimabeobachtungen vorgenommen.

Zweck der Untersuchungen

Die genannten Untersuchungen sollen dazu dienen, für beide Vergleichsflächen den Wasserkreislauf nach der Wasserhaushaltsformel

$$N = A + V + (R - B) \text{ in mm}$$

aufzuschlüsseln.

(*) Prof. Dr. W. Baden, Direktor der Staatl. Moor-Versuchsstation in Bremen, Ing. Eggelsmann, Baumeister für Wasserwirtschaft und Kulturtechnik ebenda.
Bremen, Friedrich-Missler-Str. 44 (Deutschland).

Hierin bedeuten bekanntlich :

N = Niederschlag
A = Abfluss
V = Verdunstung
R = Rücklage
B = Bedarf

$\left.\begin{array}{l} R \\ B \end{array}\right\}$ = Bodenwasservorratsänderung

Die Bodenfeuchtebestimmungen sollen zeigen, wieweit sich die wasser- und lufterfüllten Porenvolumina des kultivierten Moores von denen des wilden Moores unterscheiden.

Die mikroklimatischen Beobachtungen sollen darlegen, ob und wie Entwässerung und Kultivierung die Temperatur- und Luftfeuchteverhältnisse im Moor beeinflussen.

Oertliche Verhaltnisse

Das ursprünglich 1300 ha grosse Königsmoor liegt im Südteil des Kreises Harburg-Land an der Bahnlinie Bremen-Hamburg (53° 14' N, 9° 39' E). Nach F. Brüne ist es seinem Aufbau nach ein typisches Hochmoor mit allerdings nur geringer mittlerer Moortiefe, an vielen Stellen wird es von Sandrücken durchragt. In der zweiten Hälfte des vorigen Jahrhunderts ist es bis etwa um 1880 mittels Brandkultur landwirtschaftlich genutzt worden.

Die mittlere Geländehöhe liegt auf + 39 m N.N. Der mittlere Jahresniederschlag (ø 1913-42) beträgt nach F. Brüne 663 mm, die mittlere Jahrestemperatur (ø 1930-42) 7,9° C.

Zur Untersuchung sind die Dauerweiden C und D der Moor-Versuchswirtschaft Königsmoor mit einer ursprünglich mittleren Moormächtigkeit von 2,0 m bzw. 1,6 m sowie eine benachbarte unkultivierte Restfläche (mittlere Moortiefe rd. 1,2 m) herangezogen.

Der profilmässige Mooraufbau der Beobachtungsflächen ist bis zu einer Tiefe von 1,0 m fast völlig einheitlich Sphagnumtorf, H 2-3. Lediglich die unteren Schichtenfolgen weichen voneinander ab, was für die Vergleiche aber bedeutungslos ist.

Das verheidete Hochmoor-Oedland ist infolge verschiedener Baumassnahmen (Bahn, Wege, Gräben) während der vergangenen Jahrzehnte ungewollt vom Rande her schwach entwässert.

Die Grünlandflächen sind 1911/1912 systematisch mit Tonröhrendränen von 4,5 cm ø in Heidekrautbettung gedränt (Abstand 20 m, mittlere Tiefe 1,1 m). Sämtliche Dräne erhielten künstliches Gefälle von J = 0,2 % und münden einzeln aus. Nach den inzwischen eingetretenen Sackungen weisen die Dräne noch eine durchschnittliche Moorüberdeckung von 0,65-0,85 m auf.

Die Deutsche Hochmoorkultur trägt als Grünlandnarbe ein Lolieto Cynosuretum, das wilde Hochmoor ein Callunetum.

Nach der von O. Uhden nach wasserwirstschaftlichen Gesichtspunkten vorgenommenen Einteilung der Hochmoore sind im vorliegenden Falle die verheidete Hochmoorfläche als *vorentwassertes* Hochmoor, das Hochmoorgrünland als *kultiviertes* Hochmoor zu betrachten.

Untersuchungsmethoden

Der Niederschlag wird täglich in 1 m Höhe und am Erdboden gemessen, ausserdem ist ein Regenschreiber nach Hellmann-Fuess in Gebrauch.

Der Abfluss wird an kleinen geeichten Messwehren mittels Schreibpegel (Übertragungsverhältnis 1:1) kontinuierlich aufgezeichnet. Diese Meßstellen werden täglich kontrolliert.

Tägliche Grundwasserbeobachtungen erfolgen in 23 Brunnen in verschiedenen Entfernungen von den Gräben bzw. Dränen; zusätzlich ist auf jeder Vergleichsfläche ein Grundwasser-Schreibpegel (1:5) in Betrieb.

Während der Sommermonate wird die Verdunstung in beiden Pflanzengesellschaften mittels kleinerer selbst entworfener Lysimeter durch tägliche Wägungen bestimmt.

In den Jahren 1951/54 sind laufende Wassergehaltsbestimmungen (Gew. % u. Vol. %) in verschiedenen Bodentiefen und Zeitintervallen durchgeführt worden, wozu ein bodenphysikalisches Laboratorium in Königsmoor zur Verfügung gestanden hat. Die Bestimmung des Volumengewichtes « frisch » erfolgte nach W. Baden und H. Segeberg. Die für die Ermittlung der Substanzvolumina der Torfe notwendigen spez. Gewichte sind einer Arbeit von H. Segeberg entnommen.

Für die mikroklimatischen Beobachtungen sind grosse Aspirations-Psychrometer (nach Aßmann) benutzt worden, die während der Messungen in den verschiedenen Höhen horizontal gehalten worden sind. Diese Instrumente wie auch die sonst noch benutzten Thermometer sind vom Instrumentenamt Hamburg des Deutschen Wetterdienstes wiederholt geeicht worden.

Ergebnisse der Untersuchungen

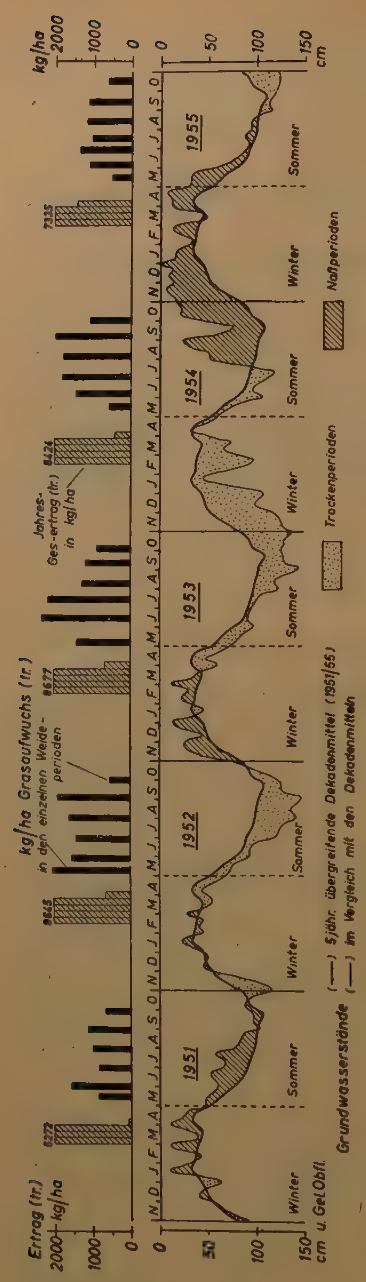
a) *Wechselbeziehungen zwischen Grundwasser, Witterung und Pflanzendecke*

Letzten Endes sind nach diesen Untersuchungen Wechselwirkungen zwischen dem Grundwassergang und der Pflanzendecke für den Wasserhaushalt bestimmend.

Zunächst, d.h. in der kälteren Jahreszeit ist das Wachstum weitgehend abhängig von der Wassersättigung bzw. dem Grundwasserstand und der auch darin bedingten Bodentemperatur. Je länger im Frühjahr hohe Grundwasserstände und damit hohe Bodenfeuchte und niedrige Temperaturen in dem Wurzelbett und der bodennahen Luftschicht darüber andauern, desto länger wird das Wachstum verzögert, desto länger hat auch in diesem Fall der Grünlandaufwuchs auf sich warten lassen. Das wird in Abb. 1 veranschaulicht, nach der die ersten Weideaustriebe in den ausgesprochen nassen Frühjahren 1951 und 1955 im Aufwuchs sehr zu wünschen gelassen haben, während er in den drei anderen Jahren dank der tieferen Grundwasserstände im Frühjahr und Vorsommer sehr viel befriedigender gewesen ist. Andererseits sind bei diesem Bodentyp mehr oder weniger tiefe Grundwasserstände bis in den März hinein offensichtlich weder für Beginn und Höhe des Frühjahrsauswuchses noch während der späteren Entwicklung und Leistung der Gründlandnarbe von nennenswertem Einfluss gewesen.

Diese Zusammenhänge sind u.E. von grosser ökonomischer Bedeutung vor allem für künstliche Vorflut (Schöpfwerke). Besagen sie doch, dass — unter den hier behandelten Bodenverhältnissen — höhere Grundwasserstände während der Wachstumsruhe (November bis März) dann nicht bedenklich sind, dass also während dieser Zeit nicht geschöpft zu werden braucht, wenn die Moorprofile genügend eng binnenentwässert (gedränt) sind. Denn nur dann wird das Wasser bei absinkenden Wasserständen in den Haupt-(Zug-)gräben auch den Flächen genügend schnell entzogen werden. Nur dann werden sie sich also auch nach anhaltend hohen Wasserständen im Frühjahr rechtzeitig erwärmen und eine rechtzeitige Entwicklung der Pflanzenbestände gewährleisten.

Mit der ansteigenden Temperatur, dem damit zunehmenden Massenwuchs und



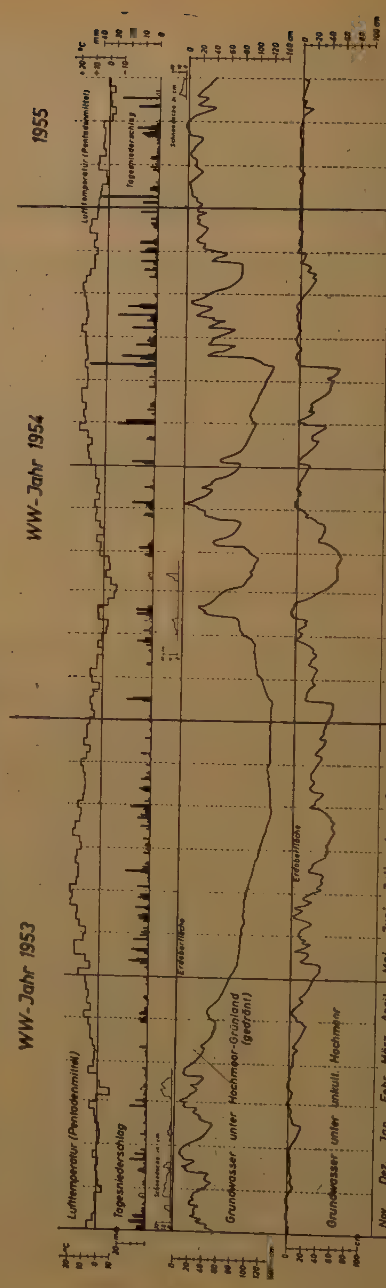


Abb. 1 — Grundwasserstände (nach tägl. Beobachtungen) auf gedräntem Hochmoorgrünland und Grasaufwuchs (Trockensubstanz) in der Moor-Versuchswirtschaft Königsmoor bei Hamburg.

Abb. 2 — Beziehung zwischen Lufttemperatur, Niederschlag und Grundwasser im Königsmoor.

der steigenden Verdunstung bestimmt die Vegetation mehr und mehr den Gang des Grundwassers. Das ist nach Abb. 2 jedenfalls für 1953 als Beispiel für Jahre mit ähnlich normalen Niederschlags- und Temperaturverhältnissen eindeutig. Denn unbeeinflusst von den recht gleichmässig verteilten Sommerniederschlägen ist das Grundwasser dank der grossen Verdunstung der davon begünstigten, massenwüchsigen Grünlandnarbe gleichsinnig bis zum September abgesunken, und zwar tiefer als 1 m unter Oberfläche. Während dieses gleichmässigen Absinkens ist die Grundwasserkurve unter dem leistungsfähigen Hochmoorgrünland auch von grösseren Niederschlägen kaum beeinflusst. Das ist nur so zu erklären, dass diese Niederschläge in dem grossen Porenraum haften geblieben und, ohne in's Grundwasser zu gelangen, danach wieder verdunstet sind.

Im Gegensatz dazu liegt die Grundwasseroberfläche in der unkultivierten, nur mit der natürlichen Hochmoorvegetation bedeckten, lediglich vorentwässerten Vergleichsfläche nicht nur wesentlich höher, sondern ihr Kurvenbild ist noch sehr viel unruhiger und ein Beweis dafür, dass bei der weit geringeren Verdunstung dieser schwachwüchsigen Wildpflanzenbestände (Ericaceen, Eriophorum, Sphagnum spec.) für darauf fallendes Niederschlagswasser nicht genügend Porenraum frei ist und schon geringe Regenmengen zu einer spürbaren Erhöhung der Grundwasserstände führen.

b) *Wasser-, Luft- und Substanzvolumen*

Die Tatsache, dass die volumenprozentischen H_2O-Gehalte im Boden unter der massenwüchsigen Grünlandnarbe von den Niederschlägen weit stärker beeinflusst werden als unter der Pflanzendecke des wilden Hochmoores ist ein gleich eindeutiger Beweis dafür, dass sie im ersten Fall dank der stärkeren Verdunstung weit stärker abgenommen haben als in der unkultivierten Vergleichsfläche mit dem geringeren Pflanzenaufwuchs. Denn dort sind die Wassergehalte durchgehend wesentlich höher, überwiegend noch so hoch, dass sie prozentisch nicht mehr erhöht werden können, da der Boden ohnehin schon das Minimum an Luftvolumen aufweist. (Abb. 3)

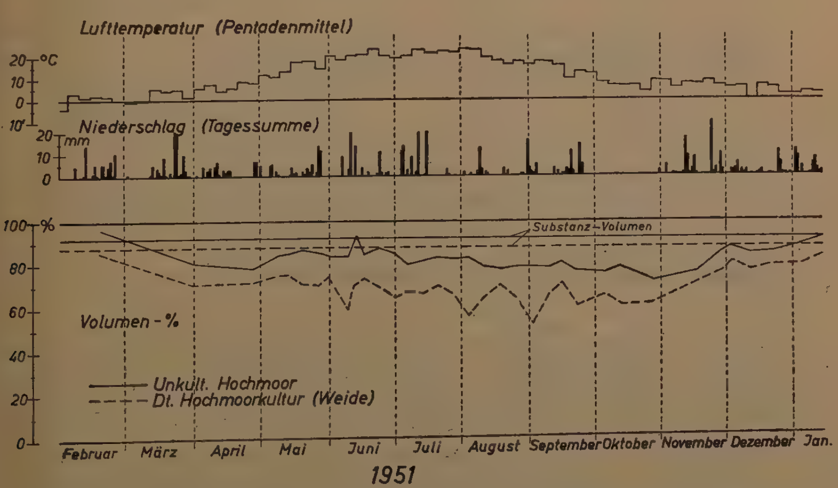


Abb. 3 — Beziehung zwischen Lufttemperatur, Niederschlag und Bodenfeuchte (Vol.-%) in der 0-20 cm tiefen Moorkrume im Königsmoor.

Der Einfluss massenwüchsiger Grünlandpflanzenbestände auf Bodenwasser- und Luftgehalt ist nach Abb. 4 bis 80 cm Tiefe deutlich spürbar. Denn der Unterschied der Gehalte an beidem zwischen der Zeit des Wachstums und der Wachstumsruhe ist auf der gedränten Hochmoorkultur ein weit grösserer als auf der nicht binnenentwässerten, nur vorentwässerten Oedlandfläche. Der massenwüchsige Grünlandpflanzen bestand hat demnach gewissermaßsen durch « Selbstdränung » die entwässernde Wirkung der Tonröhrendräne in bedeutsamer Weise verstärkt.

c) *Einfluss auf das Mikroklima*

Für die Zeit der Wachstumsruhe aber kommt die fehlende oder nur unbeträcht-

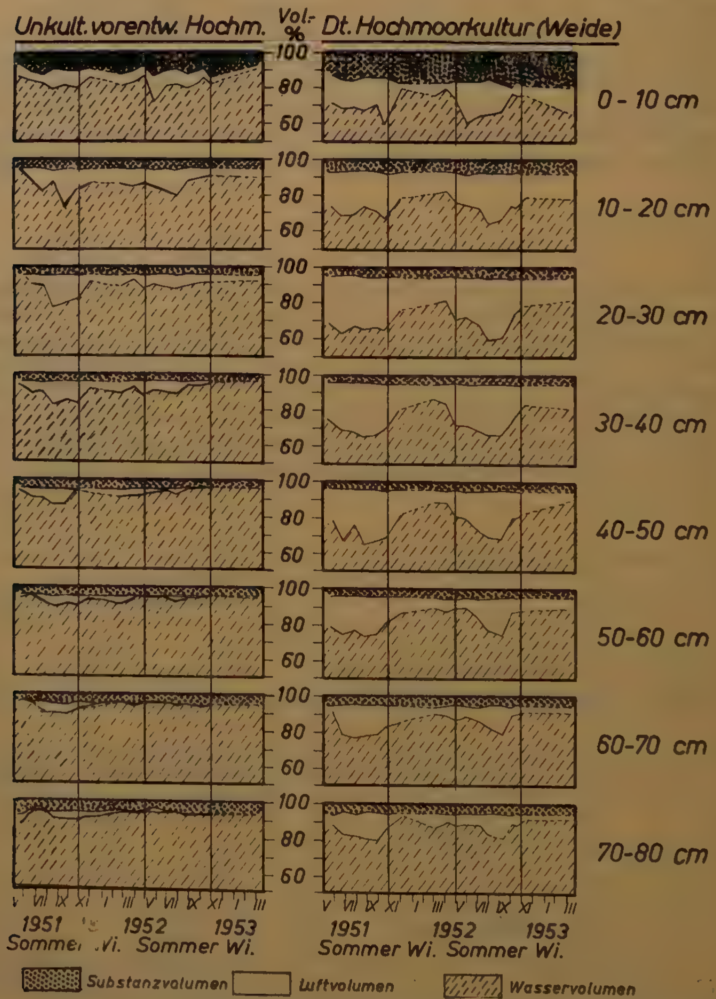


Abb. 4 — Wasser-, Luft- und Substanzvolumen in verschiedenen Bodentiefen eines verheideten Hochmoores (links) und eines Hochmoorgrünlandes (rechts) im Königsmoor.

liche Verdunstung durch die Pflanzen auf der kultivierten wie unkultivierten Fläche in der Oberfläche sehr nahen, sie zeitweilig sogar überflutenden Winterwasserständen bzw. in sehr geringen Luftgehalten zum Ausdruck (Abb. 2 und 4).

Die mehr oder weniger grosse Verdunstung wird im Gang der relativen Luftfeuchte über den verschiedenen Pflanzenbeständen der beiden Vergleichsflächen augenfällig, und zwar selbst noch in einer Höhe von 2 m über dem Erdboden. Das ist mehrfach in Terminmessungen in Erfahrung gebracht worden, von denen Abb. 5 für 2 Tage eine Vorstellung vermittelt. Danach ist die Verdunstung der Grünlandnarbe auf der Deutschen Hochmoorkultur an dem windstillen ersten Beobachtungstag

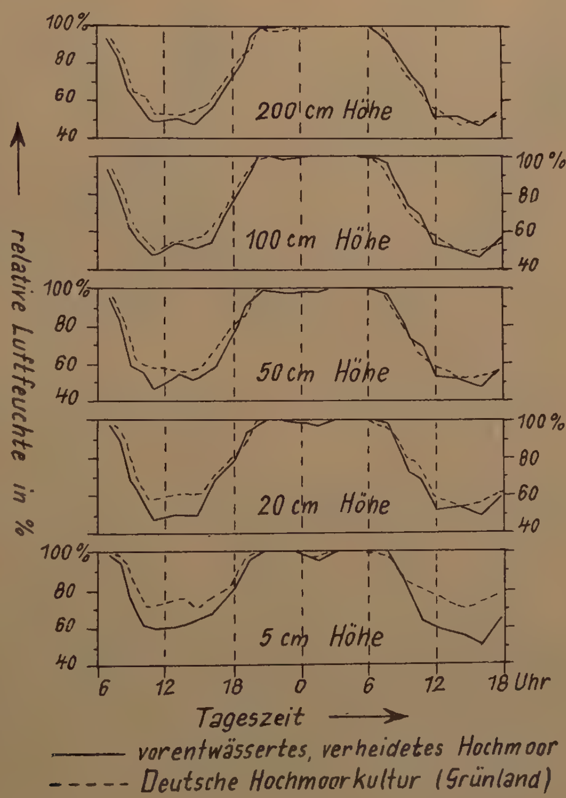


Abb. 5 — Tagesgang der relativen Luftfeuchte am 23./24.8.1951 im Königsmoor.

tagsüber merklich höher gewesen als auf dem lediglich vorentwässerten, verheideten Hochmoor. Am folgenden Meßtage ist die Überlegenheit des Grünlandes in den grösseren Höhen infolge von Turbulenzwirkungen verwischt, dabei hat eine schwache bis mässige Brise genügt, um von den angrenzenden Grünlandflächen dem Odland feuchtere Luft zuzuführen. Nach R. GEIGER war das Mikroklima der unkultivierten Hochmoorfläche an diesem Tage nicht mehr « selbständig ».

d) *Auswirkung auf den Wasserhaushalt*

Die Auswirkung dieser Wechselbeziehungen auf den Wasserhaushalt insgesamt ist in Abb. 6 für das Abflussjahr 1953 als Beispiel graphisch zusammengerafft.

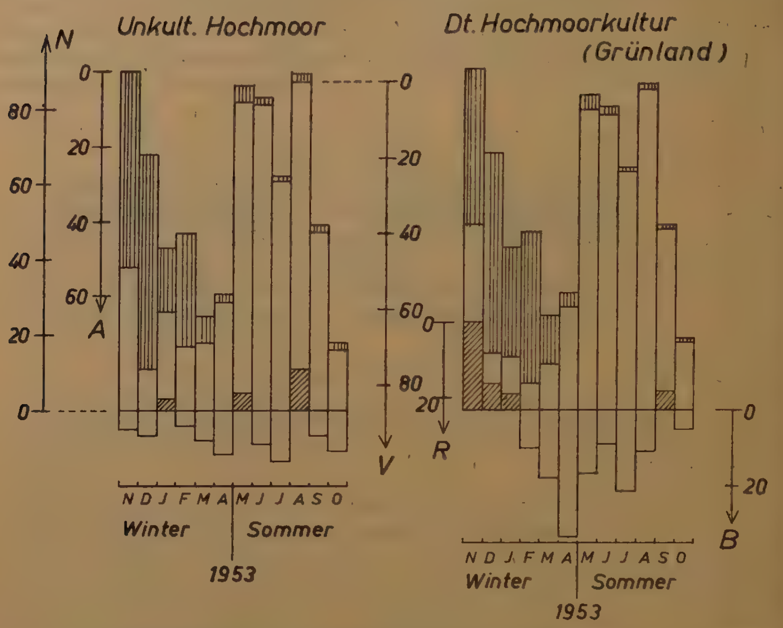


Abb. 6 — Monatssummen im Abflussjahr 1953 für Niederschlag (N), Abfluss (A), Verdunstung (V), Rücklage (R) und Bedarf (B) in mm in Königsmoor.

Danach ist der Einfluss der Vegetation leistungsfähigen Hochmoorgrünlandes auf den Wasserhaushalt im Vergleich zu dem der Wildpflanzen auf dem unkultivierten Hochmoor in mehrfacher Hinsicht ein günstiger. Denn die Verdunstung (V) ist auch danach auf der Grünlandfläche während der Vegetationszeit grösser, der Abfluss (A) im allgemeinen geringer und die Rücklage im Boden (R) im Winter beträchtlich grösser. Dank dieser grösseren Speicherung (R) auf der Grünlandfläche steht für die Verdunstung die grössere Bodenwassermenge (B) zur Verfügung.

e) *Folgerungen fur unten- und umliegende Gebiete*

Diese Zusammenhänge müssen sich verständlicher Weise letzten Endes in den Abflussverhältnissen unterhalb unkultivierter und kultivierter Hochmoorflächen in verschiedener Weise auswirken. Das haben wir in Abflussmessungen immer wieder bestätigt gefunden und treten mit einigen Messungen von vielen den Beweis dafür an (Abb. 7), dass die grösseren Abflußspitzen nicht etwa unterhalb der Hochmoorkultur mit ihrem leistungsfähigen Grünland auftreten — jedenfalls nicht während der Wachstumszeit —, sondern — ganz im Gegenteil zu der immer noch überwiegenden anderen Vorstellung — unterhalb der in Vergleich stehenden unkultivierten, nur vorentwässerten Hochmoorfläche.

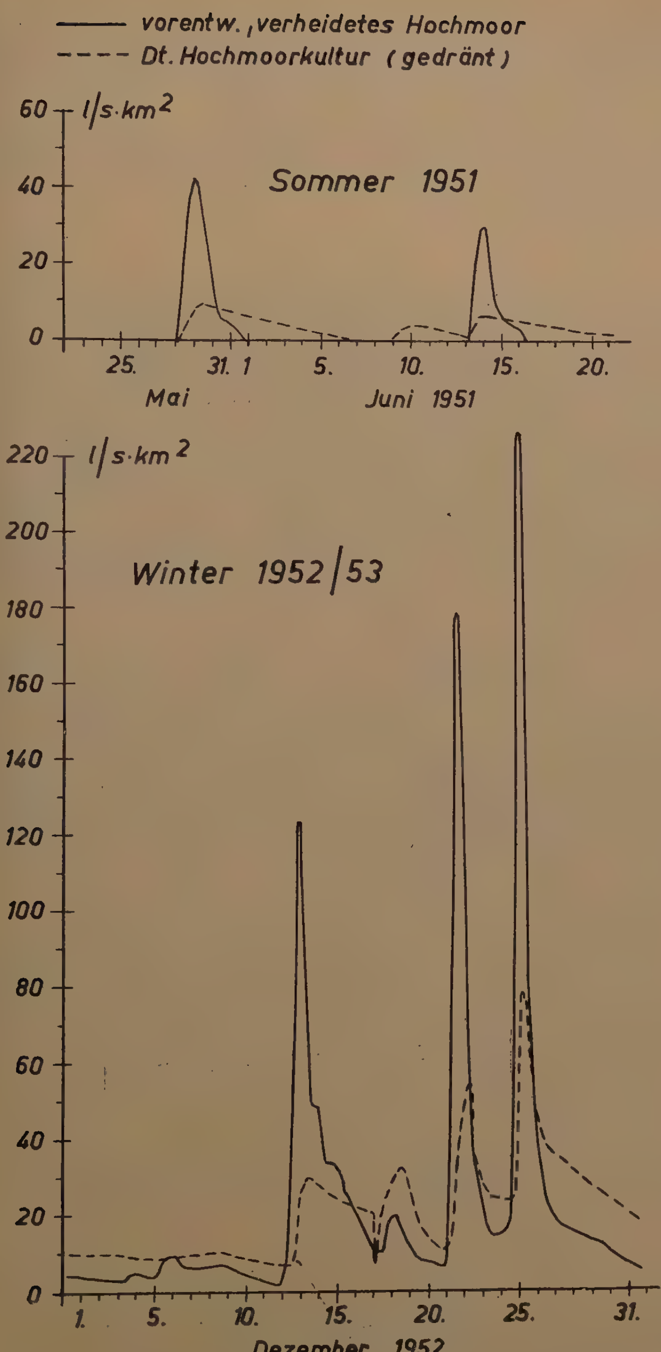


Abb. 7 — Abflußspenden-Ganglinien (in l/s. km²) im Königsmoor.

Schliesslich berechtigen uns nähere Untersuchungen auch zu der Feststellung, dass, soweit von kultivierten Hochmooren klimatische Einflüsse auf die weitere Umgebung ausstrahlen, diese nur günstiger Art sein können. Denn die höhere relative und in der Regel auch absolute Luftfeuchtigkeit über der Hochmoorkultur bewirkt — nach allgemein gültigen physikalischen Gesetzen — eine Abschwächung der Temperaturextreme zwischen Tag und Nacht (Frostgefahr). Deshalb kann die Nachtfrostgefahr in der Umgebung von sachgemässen Hochmoorkulturen mit ihrem leistungsfähigen Grünland erst recht nicht vergrössert, sondern allenfalls nur abgeschwächt werden.

LITERATUR

Baden, W. : Lehren aus den letzten Jahren für die Landeskultur. *Mitteilungen der Deutschen Landwirtschafts-Gesellschaft*, Frankfurt a.Main 1955, Nr. 29/30.

Baden, W. : Landschaftsbiologische Gestaltung von ausgebeuteten Hochmooren. *Wasser und Boden*, Hamburg (8.) 1956, S. 407.

Baden, W. & Eggelsmann, R. : Ein Beitrag zur Hydrologie der Moore. *Wasser und Boden*, Hamburg (4.) 1952, S. 244.

Baden, W. & Eggelsmann, R. : Jahresbericht über das Abflussjahr 1953 in Königsmoor. *Umdruck des Kuratoriums fur Kulturbauwesen*, Bonn 1954.

Baden, W. & Eggelsmann, R. : Über die Regelung des Wasserhaushalts bei Moormeliorationen und die dafür notwendigen Vor- und Folgearbeiten. *Wasser und Boden*, Hamburg (10.) 1958 (im Druck).

Baden, W. & Segeberg, H. : Die Probenahme und Volumengewichtsbestimmung von Moorböden. *Landw. Forschung*, Frankfurt a.Main (1) 1949, S. 147.

Brüne, F. : Fortschritte in der Bewirtschaftung von Hochmoor- und Heidesandböden. Hannover 1950.

Geiger, R. : Das Klima der bodennahen Luftschicht. 3. Aufl., Vieweg u. Sohn, Braunschweig 1950.

Segeberg, H. : Über den Zusammenhang zwischen den « Humositätsgraden » nach v. Post, den « Vertorfungsgraden » nach Keppeler und den spez. Gewichten. *Zeitschr. f. Pflanzenernährung*, Düngung, Bodenkunde, Weinheim (118.) 1956, S. 74.

Segeberg, H. & Schröder, D. : Vorarbeiten für wasserwirtschaftliche Planungen, im besonderen im Hinblick auf die zu erwartende Sackung der Mooroberfläche. Festschrift z. 75 jähr. Bestehen der Moor-Versuchsstation in Bremen, Bremen 1952, S. 93.

Uhden, O. : Verschlechtert die Entwässerung und Kultivierung der Moore die Wasserverhältnisse der Unterlieger ? *Wasser und Boden*, Hamburg (3.) 1951, S. 180.

MEASUREMENT OF RAINFALL, INTERCEPTION AND EVAPORATION LOSSES IN A PLANTATION OF SITKA SPRUCE TREES

FRANK LAW

Engineer to the Fylde Water Board, Blackpool, Lancashire, England

Abstract

A forest lysimeter has been formed by the construction of a concrete wall around one-ninth of an acre (0.045 ha) within a dense plantation of sitka spruce trees. It is thought that the underlying clay is so impermeable that no leakage of water occurs, and the runoff is collected in a tank and measured by meter.

Precipitation is measured by three gauges on poles near the top of the canopy and by gauges at ground level in adjacent open areas. The amount of water reaching ground level is determined by ten rain gauges distributed over the forest floor and by troughs which girdle some of the tree boles and collect stem flow.

During the dry period from 4 July 1955 to 8 July 1956 the precipitation on the lysimeter amounted to almost 39 inches (only 70% of the long-period average); 24 inches of this reached the forest floor and the runoff was equivalent to less than 11 inches of rain. The gross loss was therefore 28 inches, compared with 16.6 inches over the adjacent water supply cathment and 15.5 inches on a grass-covered gauge nearby.

The techniques used for measuring precipitation on the canopy and the amount penetrating same and reaching ground are described and the results analysed.

Introduction

At present, British water supply undertakings are being encouraged to afforest their water catchments and extensive areas have or are being planted with trees. Compared with other countries, relatively little research on the water balance of woodlands has been carried out in Great Britain. Some of the results obtained in other regions have indicated that a tree cover may reduce the yield of water more than a short herbaceous vegetation but the magnitude of this effect, if it occurs at all under British conditions, is largely unknown. Consequently, at the end of 1954, the author, with the permission of the Fylde Water Board, began an investigation of the water balance in a plantation of sitka spruce, *Picea sitchesis*. The results obtained in this plantation are being tentatively compared with those from small grasscovered percolation gauges and with the water catchment as a whole, which at present is mainly grassland or moorland. This problem of the effects of afforestation on water yield is important to the Fylde Water Board since ten years previously it had leased over 2,000 acres (i.e. 22%) of its Hodder catchment to the Forestry Commission. The area was mainly rough grazing but has now been almost completely planted with conifers which can be expected to produce a dense forest cover within the next 20 years.

The purpose of this paper is to describe the techniques used in examining the water balance in the spruce plantation, to analyse some of the results and to suggest the need for similar experiments in larger forest plots.

Location

The Hodder catchment is situated in the Yorkshire Pennine hills about 20 miles to the north east of Preston. Between 1929 and 1932 a number of small woodland

LYSIMETER AT STOCKS RESERVOIR

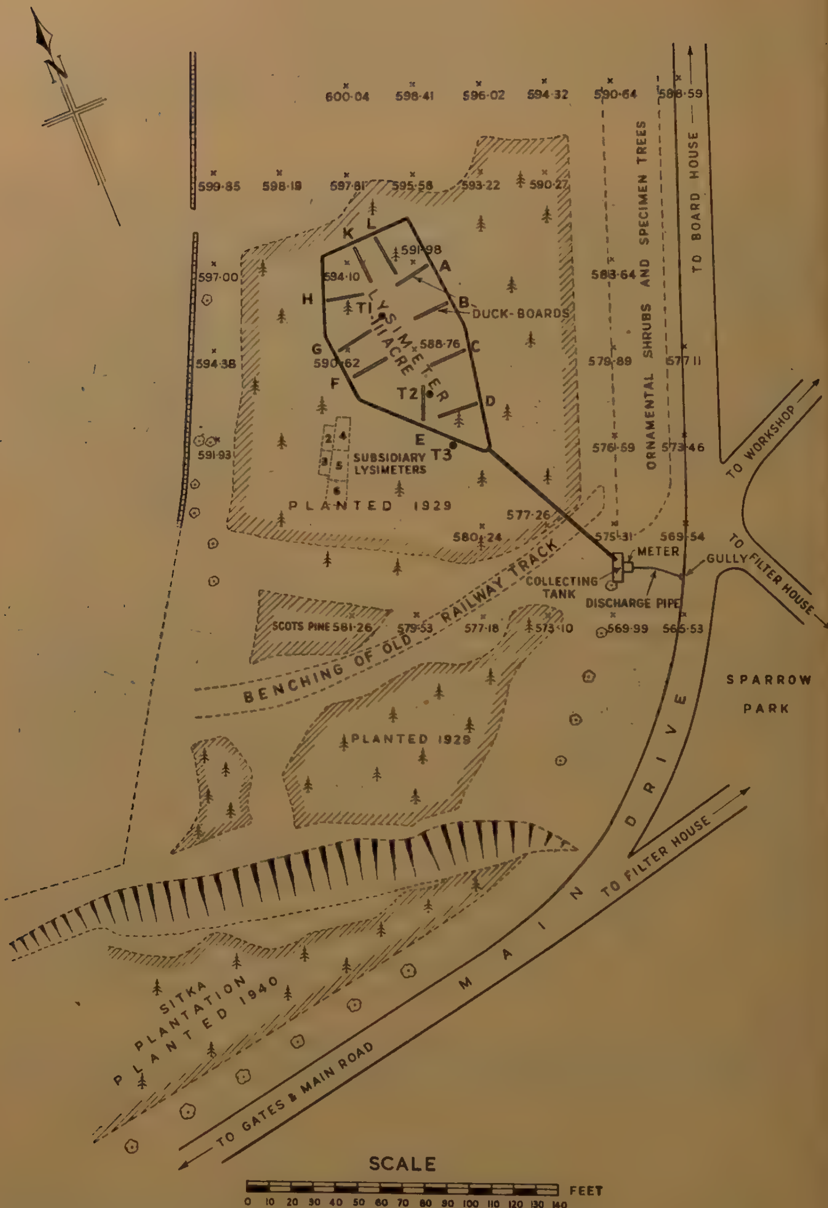


Fig. 1

blocks were planted for amenity purposes near the Stocks reservoir at Hodder and one of these plantations was selected for study. The plantation is located on a gentle south-facing slope at an elevation of about 600 feet above the sea and has a total area of 0.6 acre (0.24 ha). The plantation is in a relatively exposed situation and the average rainfall recorded at a climatological station close-by is 57 inches.

The experimental area of 0.111 acres (0.045 ha) is located more or less in the centre of the forest plot. (See Fig. 1.)

Treatment of Site

The sitka spruce was planted in 1929 using normal sylvicultural techniques. The last thinning was in 1952 when 60 trees were removed from the experimental area to leave 95 trees. The remaining trees ranged in height from 26 to 33 feet when the experiments commenced in 1955 and had an average trunk diameter of 6·5 inches at 4 feet above ground level. The current annual height increment is about 2 feet. When the plantation was thinned all the tree boles except the marginal ones were pruned. The canopy is alive down the whole length of the edge trees and forms an effective barrier to the wind, tending to isolate the central experimental area from the surrounding grassland. The wind-speed within the plot is approximately 40% of that at the Climatological Station 200 yards to the north-east.

The experimental plot was enclosed by a concrete cut-off wall approx. 9 inches wide and sunk down to a depth of about 2 feet in the soil and into the underlying clay. The wall gradually narrows above to a width of 6 inches at a height of 6 inches above ground level. The plot is roughly diamond shaped and has a fall of 1 in 10 along the longer diagonal to the lowest corner where there is an outlet through which water can flow. Field tiles were laid on the inside of the cut-off wall and surrounded with gravel. Three stone drains were intercepted during the work, and, where necessary, the intercepted drains were joined up by field drains on the outside of the wall. The top-soil is only about 12 inches deep. It is thought that the clay sub-soil is impervious and that the concrete wall effectively isolates the experimental area from sub-surface flow of water so that the experimental area functions as a lysimeter.

Observations

Complete records have been taken in the plot since July 1955, but partial data are available from March 1955. The precipitation falling upon the plot has been measured by rain gauges outside the experimental area and by rain gauges erected on poles so that they are above the forest canopy. The amount of incident rainfall penetrating to the forest floor has been determined with rain gauges beneath the trees and stem garlands to collect the water flowing down the tree trunks. Run off through the outlet at the lower corner of the lysimeter is determined by means of a flow meter. No measurements of soil moisture have been taken but the observation periods have been selected so that at their beginnings and ends the soil was probably near « field capacity ».

Measurement of rainfall upon the plot

Several rain gauges are maintained by the Board in the area around the lysimeter and three of these were selected as basic gauges for the experiment, namely:

	Catch in the calendar year 1956	Deviation from mean of three
No. 11 situated approx. 250 yds. to the North	54.5 ins.	+ 0.9%
No. 18 situated approx. 400 yds. to the S. W.	53.1 ins.	— 1.6%
No. 21 D situated approx. 200 yds. to the N. E.	54.4 ins.	+ 0.7%
Mean for 1956	54.0 ins.	

All are at sites inspected and approved by the Meteorological Office but only No. 21 D has a turf-wall surround.

The mean of these three gauges has been taken as the rainfall outside the plantation, but as the plantation is comparatively small it was thought that wind-eddies may cause some of the rain to be blown over the top. Consequently, in mid-June 1955, three rain gauges were fixed at the tops of poles within the plantation canopy, the water therefrom being led down tubes fastened to the poles to containers at the base.

For the first nine months of the experiment these tree-top gauges consisted of the top portions of Meteorological Office, Mark II rain gauges, i.e. in external appearance they consisted of a cylinder 5 inches diameter by 7 inches deep.

The first, T1, was on a pole only 21 feet 6 inches high because it was situated in a clear space (approximately 5 feet diameter at the base of the canopy and wider a ove) but the other two were on higher poles, T2 being 29 feet high and T3 27 feet 6 inches high.

Over this first period from June 1955 to early March 1956, the catch of the tree-top gauges averaged 88% of the three outside gauges, whilst between themselves T2 was consistently lowest and T3 the highest, the ratio T1/T2 being 1.02 and T3/T2 1.05.

Dr. H. R. Mill (1900) had found that the rainfall caught by a plain gauge at 10 feet above ground level was 90 to 91% of that at the standard level of 1 foot above the ground, and at 25 feet above ground level about 75% to 88%, but when the experiment commenced it was not known what was the relative exposure of rain gauges situated at 20 to 30 feet above ground level within a plantation canopy. In March 1956, therefore, a replica of the tree-top gauges was fixed at 10 feet height at an experimental rain gauge site nearby (known as No. 10 site). At the same time T3 was fitted with a type of nipher shield, and a similarly shielded gauge was set up at No. 10 site.

The ratio between the catch of T3 and the mean of T1 and T2 had previously been 1.04, but after the change to nipher shield the ratio jumped to 1.16, so it appeared that the shield caused an increase of about 12% in the catch of T3. Over the same period th; shield;d gauge 10 feet high at No. 10 site (No. 10E) caught 8% more than did No. 10F which was the replica of T1 and T2, but 10 feet high in the open. Consequently, it appeared that the exposure of the tree-top gauges was 50% greater than the equivalent of 10 feet high above the ground in the open, and that the corrections to be made should be 50% greater than those found at No. 10 site — namely 3.3% deficiency on 10E and 12.0% deficiency on 10F, relative to the basic turf wall gauge No. 10.

Uplifting the catch of T3 over the relevant period (43.2 inches) by 1.5 times 3.3% gave 45.4 inches, whilst uplifting T1 and T2 (36.8 inches) by 1.5 times 12.0% × 88/82 (to allow for the more serious adjustm nt) gave 43.9 inches as compared with 44.9 inches for the average of the three outside gauges for the same period. The factor 88/82 is derived from (100-12) divided by (100 — 1.5 × 12).

It appeared, therefore, at the end of December 1956, that the rainfall on the plantation was *not* appreciably reduced from the average rainfall utside the plantation.

Since August 1956, however, it had been noticed that the ratio between the tree-top gauges and the outside gauges had been lowering. This may be due to growth of the trees (which as previously stated is estimated a 2 feet per annum), and on the 7th January 1957, T1 was lifted 5 feet to test this theory.

From 7th January to 17th February 1957 the catches were:

Mean of 3 outside gauges	8.23 inches
Tree-top gauge T1	7.56 inches
Tree-top gauge T2	6.38 inches
Tree-top gauge T3	7.33 inches.

The ratio T3/T2 remained approximately as before, at 1.15, but T1/T2 jumped from 1.02 to 1.19.

The height of T1 was still less than T2 and T3, so on 18th February 1957 it was lifted a further 5 feet, to determine whether there could be an optimum ratio of catch in a tree-top gauge. At the time of writing insufficient information has been obtained to make any reliable observations thereon, but it would seem that in the early stages of the experiment T1 and T2 were being deprived of rain by nearby branches of the trees, whilst T3 was giving somewhat similar results because it was more exposed to the prevailing winds than were the other two. It seems possible that the slender tops of the trees cause a considerable amount of turbulence and that this turbulence is so great that a rain gauge makes little extra difference — consequently the necessity for shielding of the gauge may not be as great as was thought earlier in the experiment.

It does seem definite, however, that the «tree-top» gauges should be *above* the canopy.

In collaboration with Dr. J. D. Ovington of the Nature Conservancy Organisation, three further tree-top gauges have now been installed. These have a different nipher shield without a horizontal «brim», because it has been found at the No. 10 site that elevated shielded gauges with «brims» catch excessive amounts when high winds coincide with «drizzly» rain — and the more complicated the nipher shield the greater the excess catch.

The poles carrying these three additional gauges are adjustable for 1 foot increments of height, so as to facilitate experiments within and just above the canopy. As a check three similarly shielded gauges are being erected at No. 10 site, with the rims 18 inches, 10 feet and 30 feet respectively, above ground level. Reliable conclusions from these last additions to the equipment cannot be expected for some considerable time, but it may be possible to give some data as an addendum to this paper when published.

In the early stages of the experiment, as a temporary measure, the rain falling on the canopy was estimated as the mean of the six gauges — three outside and three tree-top. This definitely appears to give a low estimate, but has been retained for this paper.

Measurement of rainfall under the canopy

At ground level within the lysimeter ten Meteorological Office, Mark II rain gauges are being used to measure the water dripping from the trees. These ten gauges have been moved about in random manner from time to time in order to overcome the variation in the catches depending upon whether or not they are receiving drips from the branches of the trees.

At first the movement was made at the earliest convenient time after one inch of rain had been measured outside and the gauges were placed randomly by the observer, but latterly this movement has been more frequent (approximating to every half inch of rain outside the plantation) and the spacing of the gauges has been to a more definite plan, but still with attempted randomness.

To prevent damage to the plantation floor by trampling in wet weather, ten wooden duckboards (caillebotis), each 20 feet long were laid down in December 1955, and, since then, each of the ten gauges has been placed alongside its duckboard at one of 36 alternative points marked off on the duckboard, 18 on one side and 18 on the other. The line of each duckboard was selected so that at some points the gauges would be near to a trunk, and at other points remote from the trunks. In order to ensure that the placing of the gauges is random, the point at which the gauge is placed is selected out of the 36 alternatives by two throws of a dice. It was thought that this arrangement would give a more truly random pattern of rain gauges and would obviate bias on the part of the observer, but results have not confirmed this as will be seen from Table 1.

In 1955 the coefficient of variation of the catches in the ten gauges in any one pattern varied from 16% to 63% with an average of 33%. When the patterns were aggregated the coefficients of variation dropped to 9.8% for the first 11 patterns and 9.4% for the subsequent 13 patterns, whilst for the total 24 patterns the coefficient of variation was reduced to 6.4%. It will be seen that these are approximately in inverse proportion to the square root of the number of patterns aggregated — i.e. what would be expected by statistical reasoning if the patterns were random.

On the other hand in 1956, with the gauges set out randomly alongside the 10 duckboards, whilst the coefficients of variation for individual patterns still ranged from 20% to 65%, with an average of 38%, the coefficients for aggregates of patterns have been much higher than would be expected from the inverse square root ratio — indeed after 54 patterns the coefficient of variation was 11.8%, whereas it would have been only 5.4% for true randomness. In other words there has been more bias with the duckboards than previously; but though there is this obvious bias and variation between the gauges, as the duckboards are fairly uniformly spread over the lysimeter area, it is considered the average may be more reliable than the standard error of the mean would suggest. Incidentally, it would appear that duckboards B and H are under denser foliage than the others and that the interception is, therefore, greater.

Since mid-March 1957 the method of siting the gauges has been amended by making a further throw of the dice and placing the gauge concerned at a distance in feet from the duckboard equal to this third throw of the dice. The result will be that the gauges will sample an area about 13 feet wide by 20 feet long, and the 10 gauges will therefore, be sampling a total of 290 square yards out of the 537 square yards within the lysimeter wall. If circumstances permit, the results of this amendment will be given in an addendum when the paper is published.

To demonstrate the variability between the catches of the gauges in any one pattern those for the period 9 July - 26 August 1956 (a particularly wet period) are set out in Table 2.

Measurement of Water Flowing down the Tree Stems

The amount of water flowing down the tree stems has been measured by fixing garlands round the trunks of some of the trees at chest height, and leading the flow therefrom into containers alongside the tree. At the start of the experiment three of the trees were thus garlanded, but in view of the variation in the amount of water

TABLE 1

	No. of Patterns	Catches by Plantation Floor Gauges — Inches											Coeff: of Variation %
		A	B	C	D	E	F	G	H	K	L	Mean	
16 Mar. - 3 July 1955	11	7.39	9.00	6.61	8.79	8.67	9.01	8.54	8.69	7.13	7.97	8.18	9.8
4 July - 31 Dec. 1955	13	11.13	12.78	12.18	11.84	11.93	10.58	10.61	9.03	11.15	10.87	11.22	9.4
Sub-total 1955	24	18.52	21.78	18.79	20.63	20.60	19.59	19.15	17.72	18.38	18.84	19.40	6.4
1 Jan. - 8 July 1956	22	11.99	9.68	10.62	10.83	11.04	10.51	9.24	7.80	8.99	11.64	10.23	12.6
9 July - 26 Aug. 1956	12	8.67	7.64	10.83	10.75	10.91	8.84	13.5-	8.73	10.03	8.88	9.88	17.1
27 Aug. - 31 Dec. 1956	20	10.11	8.55	10.89	11.38	12.49	7.83	12.05	8.86	8.69	11.51	10.24	16.2
Sub-total 1956 (Duckboards)	54	30.77	25.87	32.34	32.96	34.44	27.18	34.79	25.39	27.71	32.03	30.35	11.8
Grand Total	78	49.29	47.65	51.13	53.59	55.04	46.77	53.94	43.11	46.09	50.87	49.75	7.7

TABLE 2

Plantation Floor Gauge Catches

1956		A	B	C	D	E	F	G	H	K	L	Mean	Coeff. of Variation
													%
July	9 - 15	.04	.64	.32	.60	.46	.30	.22	.36	.03	.20	.32	65
	16 - 23	.12	.21	.24	.09	.15	.06	.27	.06	.06	.12	.14	56
	24 - 27	.60	.39	1.03	1.90	1.45	.77	1.59	.82	1.35	.91	1.08	44
	28 - 29	.44	.73	.83	.67	.71	.36	1.02	.33	.89	.55	.65	35
	30 - Aug. 1	1.19	1.73	1.16	1.29	2.16	1.34	3.40	.88	2.26	.94	1.63	48
August	2 - 6	.67	.55	.93	1.11	.59	1.41	1.00	.72	.58	.50	.81	37
	7 - 12	1.06	.74	1.35	1.29	1.48	1.45	1.26	1.50	.94	1.51	1.26	21
	13 - 15	1.08	.36	.67	.98	1.33	.56	1.85	1.23	.53	1.13	.97	47
	16	.36	.53	1.01	.27	.45	.52	.35	.52	.40	.59	.50	51
	17 - 19	.70	.80	1.50	.83	1.15	1.21	.78	.70	.96	.97	.96	27
	20 - 24	1.87	.79	1.58	1.46	.55	.72	1.44	1.15	1.58	1.14	1.23	35
	25 - 26	.54	.17	.21	.26	.43	.14	.32	.46	.45	.32	.33	42
Totals for Period 9 July - 26 Aug. (12 «patterns»)		8.67	7.64	10.83	10.75	10.91	8.84	13.50	8.73	10.03	8.88	9.88	17.1

collected from tree to tree the number of trees sampled was increased to five from 2nd February 1956, the results being shown in Table 3. The ratios between the water collected for the individual trees is very great, but the reasons for these differences are not apparent. The amount of water flowing down the stem is, however, small compared with the total amount of precipitation. In the 18 months during which observations have been made, stem flow averaged only 7% of the rain falling on the trees. It is hoped that it will be possible to make more measurements of water-flow down the tree stems in the future.

Throughfall and Interception

The sum of the drip from the trees and the flow down the stems is known as «Thr ughfall» and the difference between the estimated rainfall over the canopy and the throughfall is termed «Interception».

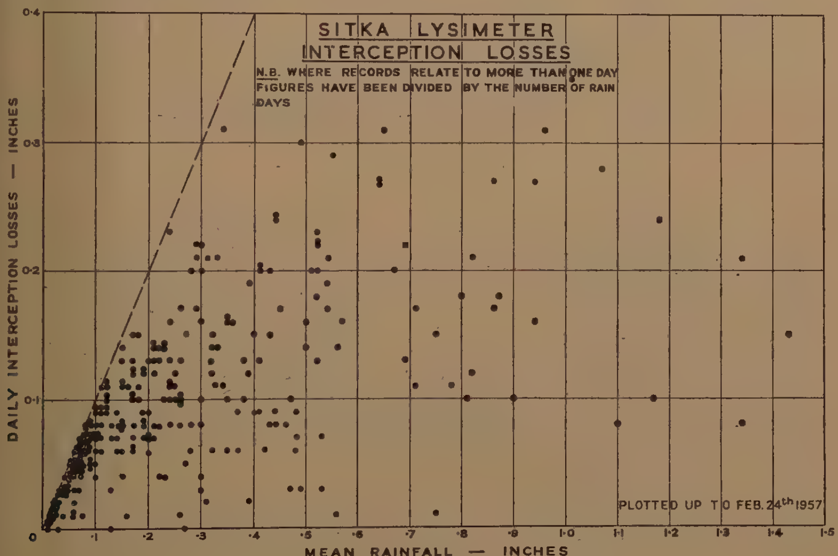


Fig. 2

In Fig. 2 the daily interceptions have been plotted against estimated rainfalls on the canopy. It will be seen that it is a scatter diagram with no definite trend.

On the other hand if the values are grouped into rainfalls on the canopy of 0-.1 inch, .11 to .20 inch . . . . .51 to .60 inch and .61 inch and upwards for the summer and winter 6-months periods we obtain the results shown in Fig. 3, with a solid curve through the aggregate means. It will be seen that, on the average, the amount intercepted is not a constant ratio of the rainfall — it is greater with light rains of short duration than with heavy or prolonged rains. With falls of 0.2 inches per day the interception averages 50%, whilst for 1.0 inch per day it is only 19%.

It is impossible to say at this stage what significance there is in the departures of the seasonal means from the mean line, except that the interceptions in a dry summer seem to be the highest — which is the worst from a water supply point of view.

TABLE 3

Comparison of Catches of Tree Bole Gauges

	Tree Bole Gauge Catches-inches					Means		Estimated Tree-top Rainfall ins.	Mean of 3 tree-bole as percentage of rainfall
	B1	B2	B3	B4	B5	of 3 B1, B2, B3	of 5 B1-B5		
1955 July 4 - Dec. 31	2.06	1.03	1.31	—	—	1.47	—	19.73	7.5
1956 Jan. 1 - Feb. 1	.64	.37	.32	—	—	.44	—	5.45	8.1
Feb. 2 - July 8	1.07	.58	.66	.95	.18	.77	.69	13.58	5.7
July 9 - Aug. 26	1.13	.79	.69	1.23	.44	.87	.86	14.76	5.9
Aug. 27 - Dec. 31	1.95	.81	1.18	2.04	.37	1.31	1.27	16.68	7.8
Totals 2 Feb. - 31 Dec.	4.15	2.18	2.53	4.22	.99	2.95	2.82	45.02	6.3

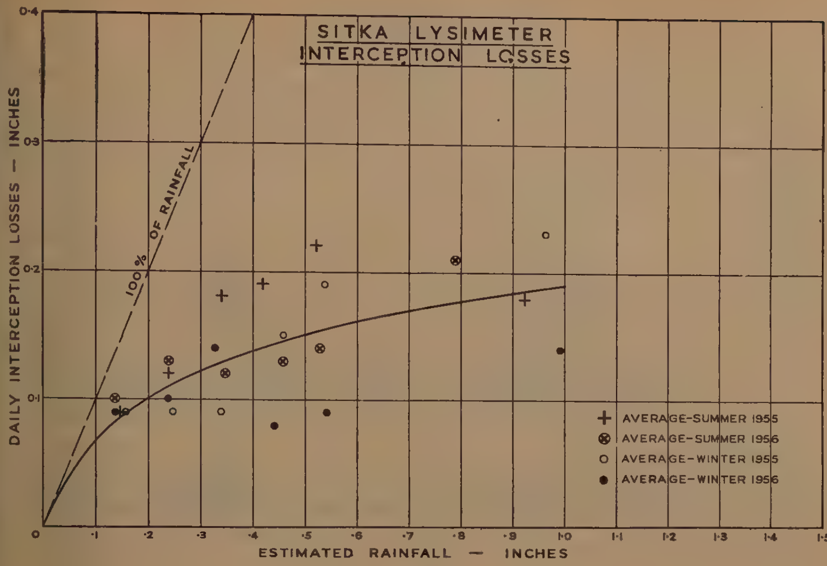


Fig. 3

On the other hand, part (if not the whole) of this apparent effect may be due to increasing shelter of the tree-top gauges as the trees became taller. This would lower the average value for the six gauges relative to the true rainfall on the plantation, but further investigation of this matter will have to await more accurate determination of the rainfall upon the canopy.

It is, however, noteworthy that the interceptions in the winter of 1955 were as high as those of the summer of 1956, despite the fact that theoretically the drying potential is vastly greater in summer than in winter.

Measurement of Runoff

From the lowest corner of the plot wall a six inch pipe has been taken to a 1,200 gallon(5, 450 litre) storage tank from which the drainwater is lead through a 2 ins. diameter semi-positive waterworks meter. Between the storage tank and the meter there is a strainer to prevent the conifer needles from choking the meter, and, on the downstream side of the meter the pipe is arranged so that the meter does not come into operation until the tank is approximately one-third full, so that the water cannot dribble through the meter. Each morning prior to reading the meter the observer lowers this flexible pipe so that the tank is fully drained off as quickly as possible. A similar meter has been fixed to the overflow from the tank, but the overflow has never yet come into operation during the course of the experiment.

The weekly runoffs from the lysimeter are shown in Fig. 4, along with the corresponding runoff from the catchment as a whole and from the grasscovered gauge A21. The weekly rainfall on rain gauge 21D is also shown to a smaller scale, but it should be noted that both runoffs and rainfalls are not strictly comparable because the general rainfall on the catchment is greater than that of gauge 21D, which in turn is greater than the estimated rainfall on the top of the plantation canopy.

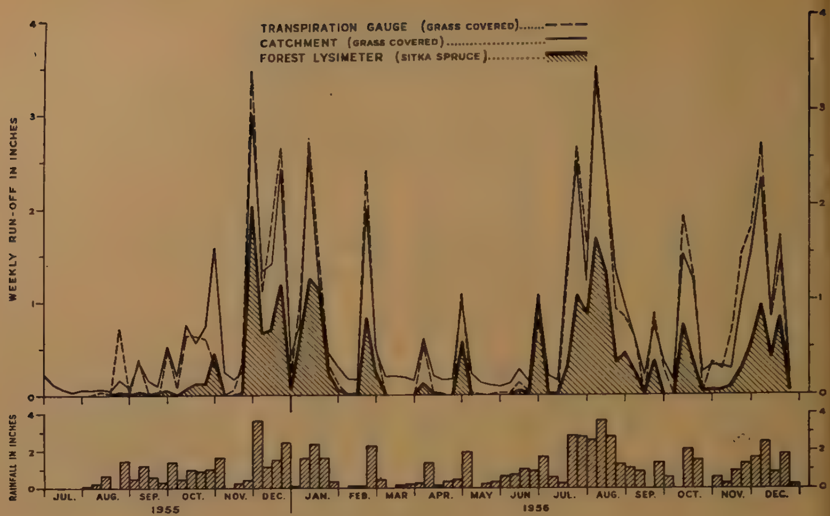


Fig. 4

It will be seen that the transpiration gauge and catchment runoffs are quite similar but the lysimeter runoffs are far less.

Preliminary Results

Preliminary results have already been published (Law 1956) and these are set out in Table 4, together with the corresponding results for the calendar year 1956. The first 12 months period was quite dry, with rainfall amounting to only 70% of the Meteorological Office estimate of the long-period average, and this has been divided into three portions, terminal dates being times when the soil moisture was thought to be at «field capacity»:

24 weeks	4 July to 18 December 1955
12 weeks	19 December to 11 March 1956, and
17 weeks	2 March to 8 July.

The calendar year 1956 commenced dry, but July and August were wet—the latter month particularly so— and the year's rainfall was approximately 95% of the long period average.

In addition to the data for the Sitka plantation lysimeter there are also in Table 4 corresponding figures for evaporation from the evaporation tank and percolation gauges in the Climatological Station 200 yards to the north-east of the lysimeter, and the rainfall, runoff and losses over the catchment as a whole.

Noteworthy points in this table are:

(*a*) During the dry period from 4 July 1955 to 8 July 1956 the precipitation on the lysimeter amounted (in round figures) to 39 inches, but of this only 24 inches reached the forest floor and the runoff was less than 11 inches. The gross loss was, therefore, 28 inches, compared with 16.6 inches over the catchment area and

TABLE 4

Stocks Reservoir, Slaidburn, Yorkshire (W. R.)

Summary of data in successive periods from 4 July 1955 to 8 July 1956 and Calendar Year 1956

	12 months' Period with approximately 70% of average annual rainfall				Calendar year 1956 with 95% of average annual rainfall
	4 July to 18 Dec.	19 Dec. to 11 Mar.	12 Mar. to 8 July	TOTAL 4 July/55 to 8 July/56	
No. of Weeks	24	12	17	53	52
	ins.	ins.	ins.	ins.	ins.
Sitka Plantation Lysimeter					
(1) Mean of 3 Outside Gauges	17.29	12.68	10.96	40.93	53.96
(2) Mean of 3 Tree-top Gauges	15.35	11.06	10.18	36.59	46.99
(3) Estimated Mean Rainfall	16.32	11.87	10.57	38.76	50.47
(4) Estimated Interception	5.87	4.25	4.51	14.63	16.78
(5) Estimated Throughfall	10.45	7.62	6.06	24.13	33.69
(6) Lysimeter Runoff	3.55	6.30	0.91	10.76	16.14
(7) Gross Losses	12.77	5.57	9.66	28.00	34.33
(8) Net Losses without Interception	6.90	1.32	5.15	13.37	17.55
Experimental Results in Climatological Station					
(9) Evaporation from 6 feet Square Tank	8.98	(1.00)	8.40	18.38	16.97
(10) Losses from Grass-covered Percolation Gauge A21	7.45	(0.22)	7.86	15.53	15.70
(11) Losses from Grass-covered Percolation Gauge (kept irrigated) (Composite figures based upon Gauges B21, C21 and E21)	10.52	(1.05)	8.83	20.40	17.07
(12) Calculated evaporation from Water Surface by Penman's 1954 «Rome» formula	9.93	0.29	10.38	20.60	17.48
(13) Runoff from Percolation Gauge A21	10.11	12.83	2.61	25.55	39.34
Catchment Area of 9,253 Acres					
(14) Estimated General Rainfall	18.66	14.49	11.66	44.81	60.15
(15) Runoff	10.85	12.36	5.02	28.23	40.72
(16) Estimated losses	7.81	2.13	6.64	16.58	19.43

NOTE: The results in brackets are doubtfull, possibly due to melting snow and other causes.

15.5 inches on the grass-covered percolation gauge A21. In other words the losses in the lysimeter were 11 or 12 inches higher.

(*b*) The nett losses in the lysimeter (line 8) in the warmer periods are less than elsewhere (lines 9, 10, 11 and 16) — so it would appear that for considerable periods the trees were short of moisture, or on certain days the trees were not transpiring because the available energy was being used up in the evaporation of intercepted rainfall. In the calendar year 1956, however, the nett losses are greater than those of the percolation gauge A21 and it would seem that at 8 July 1956 there was still a soil moisture deficiency in the lysimeter, but that at no time during the year was there a deficiency great enough to restrict the transpiration rate, as occurred apparently in 1955.

(*c*) During the winter period 19 December 1955 to 11 March 1956 the nett loss in the lysimeter was only 1.32 inches, so it would not seem that there was much leakage, if any at all, through the clay base. Losses from the catchment and from the experimental gauges were of the same order, although there are certain unexplainable differences in the latter, probably due to melting snow, etc., but possibly due to the fact that gauges A21 and B21 have sloping surfaces facing into the prevailing wind (and A21 more steep than B21 at that time) and the rainfall on same not being measured absolutely accurately. This difficulty of measuring rainfall on a sloping surface has not yet been overcome and additional percolation gauges C21 and E21 have been formed with level surfaces.

Effect upon the Yield of the Catchment

The yield of a catchment is normally estimated in Great Britain as the runoff in a year having a rainfall of 80% of the average. In the case of the Stocks Reservoir catchment, where the experiments have been carried out, the average annual rainfall is estimated to be 62.9 inches and the nominal yield is therefore (80% of 62.9 inches) minus (17.5 inches evaporation losses) = 32.8 inches. An increase of 11 inches in the losses would therefore reduce the yield by one third. The nett effect is worse, however, because usually between 20% and 33% has to be given to the stream as compensation water, and the effective loss for supply purposes, resulting from 11 inches increase of the losses, is 42% to 50%, depending on the ratio of compensation water.

Watertightness of the Lysimeter Base

It is thought that the clay sub-soil of the lysimeter is impervious but there can be no certainty. As a check two subsidiary lysimeters L2 and L3, have been constructed to the south-west — L2 contains two tree stumps, and L3 one tree stump and one ill-shaped tree which is to be cut down. These subsidiary lysimeters have been surrounded by concrete walls similar to that of the main lysimeter and the intention is to cover them with plastic sheeting and then irrigate with measured quantities daily. If the differences between the irrigation and the runoff are significant, then the same may apply to the main lysimeter.

Futur Work

Alongside L2 and L3, three other subsidiary lysimeters have been formed, L4, L5 and L6, but each of these contains two good trees, and it is hoped, by suitable covers of plastic sheeting and irrigation, to estimate —

(*a*) what transpiration can take place if the trees are adequately provided with moisture;

(*b*) to what extent transpiration is reduced when intercepted moisture is being evaporated.

Consideration is also being given to the practicability of gauging one of the reservoir feeders, in the drainage area of which a considerable proportion of the planting by the Forestry Commission has taken place. This would, however, involve considerable expense and it would be another fifteen years before worthwhile results would be available.

The author hopes that in the near future the Nature Conservancy, the Forestry Commission and other interested bodies will commence similar experiments in larger forests, because it would seem that the main possibility of error in the present experiments is that they have been carried out in a small plantation, and in a large forest the evaporation of moisture hanging on the trees may not be so rapid.

REFERENCES

LAW, F. (1956) «The effect of Afforestation upon the Yield of Water Catchment Areas», British Association for the Advancement of Science, Sheffield, 1956, printed in *Journal of the British Waterworks Association.* November, 1956. pp. 489-494.

MILL, H. R. (1900) «The Development of Rainfall Measurement in the last Forty Years», in a publication entitled British Rainfall, 1900.

LE ROLE DE LA VÉGÉTATION DANS L'ÉPUISEMENT DES RÉSERVES EN EAU DU SOL

Marc HALLAIRE
France

RÉSUMÉ

Dans l'étude des bilans hydriques, on admet généralement que, si le sol est suffisamment humide, l'évapotranspiration se confond avec l'évapotranspiration potentielle définie par les facteurs du climat. Par contre, lorsqu'est atteint un certain déficit critique Dc, estimé à 100 mm par la plupart des auteurs, l'eau qui demeure dans le sol serait inapte à gagner l'atmosphère et l'évapotranspiration serait dès lors limitée aux apports des précipitations.

Des déterminations systématiques d'humidité du sol en plein champ ont tout d'abord permis de vérifier que le déficit en eau du sol peut atteindre des valeurs beaucoup plus élevées sous couvert végétal qu'en sol nu : ces différences tiennent au fait que le mulch, qui se forme naturellement lors du dessèchement du sol, ne freine le passage de l'eau vers l'atmosphère qu'en l'absence de couvert végétal.

En outre, le déficit critique Dc observé sous végétation peut varier dans des proportions importantes autour de la valeur moyenne admise de 100 mm : dépendant évidemment des propriétés hydrodynamiques du sol (capacité de rétention), il est également fonction de la profondeur utile du système radiculaire, cette dernière pouvant aller de 20 à plus de 80 cm pour des plantes annuelles ou herbacées.

On sait que le sol peut retenir par capillarité une certaine quantité d'eau et présenter ainsi en fin de saison pluvieuse et après cessation de drainage une humidité particulière : la capacité de rétention. Cette réserve d'eau joue le rôle de volant hydrique dans le cycle hydrologique annuel : elle assure en période sèche, et jusqu'à une certaine limite, le maintien de l'évaporation et de la transpiration végétale tandis qu'en période pluvieuse, il lui faut tout d'abord être reconstituée pour que l'écoulement de l'eau puisse se faire en profondeur.

Cette réserve a une limite et le but de cette étude est d'en préciser la valeur compte tenu du sol et de la végétation. Il sera bon toutefois de rappeler au préalable les quelques notions qui permettent de dresser un bilan hydrique et de montrer comment celui-ci dépend de la quantité d'eau susceptible d'être ainsi emmagasinée dans le sol pour être ensuite livrée à l'atmosphère par le jeu de l'évaporation ou de la transpiration végétale.

I — ÉVAPOTRANSPIRATION POTENTIELLE, ÉVAPOTRANSPIRATION RÉELLE, DÉFICIT MAXIMUM EN EAU DU SOL ET BILAN HYDRIQUE

L'évaporation de l'eau, qu'elle se situe au niveau du sol ou des organes foliaires, exige une soixantaine de calories par dg. En d'autres termes, l'évapotranspiration d'une tranche d'eau de 1 mm absorbe 60 calories/cm². Dès lors, si le sol est abondamment pourvu en eau, on conçoit que le facteur limitant de l'évapotranspiration soit cet apport énergétique, essentiellement défini par la radiation globale ou d'une façon plus générale par les facteurs du climat. On comprend également que plusieurs auteurs (PENMAN, THORNTHWAITE, BLANEY et CRIDDLE) aient pu établir des formules donnant cette évapotranspiration en fonction des données climatiques. Il faut toutefois souligner que les formules en question indiquent un maximum, correspondant au cas où l'eau ne fait pas défaut; elles donnent la valeur de l'évapotranspiration potentielle Ep.

Cette évapotranspiration, lorsqu'elle excède les apports dus aux précipitations P, entraîne le dessèchement du sol dont l'humidité décroît alors au-dessous de la capacité de rétention. Il peut arriver que la sécheresse du sol étant à son tour facteur limitant, l'évapotranspiration réelle E_R devienne inférieure à Ep. L'expérience montre en effet que lorsqu'un sol a atteint un certain déficit en eau (le déficit représentant la quantité d'eau, en mm, à apporter pour que l'humidité devienne égale à la capacité de rétention à toute profondeur), les pertes par évaporation et transpiration diminuent pour tendre assez rapidement vers zéro.

Schématisant le phénomène, Thornthwaite admet qu'au niveau d'une végétation couvrant bien le sol, l'évapotranspiration réelle E_R est égale à Ep tant que le déficit est inférieur à 100 mm. Ensuite, le sol étant impropre à céder des quantités d'eau supplémentaires, le déficit demeurerait égal à cette valeur de 100 mm et l'évapotranspiration réelle serait limitée à la hauteur des précipitations P. Puis, à partir de l'automne dans les régions tempérées, lorsque les pluies l'emportent sur l'évapotranspiration potentielle, l'écart P — Ep contribue à reconstituer des réserves en eau et le déficit diminue. Enfin quand les réserves sont reconstituées (déficit nul). l'excès des pluies par rapport à l'évapotranspiration draine pour gagner les nappes d'eau profondes et s'écouler vers la mer. Ce schéma conduit à une représentation simple du cycle annuel de l'eau (voir le graphique de la fig. I relatif à la région parisienne).

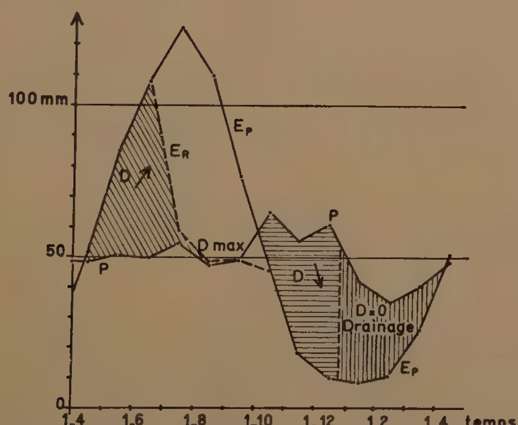


Fig. 1 — Cycle annuel de l'eau — Versailles — Année normale — (L'évapotranspiration potentielle Ep est ici calculée à partir de la formule de THORNTHWAITE — le déficit maximum D_{max} est supposé égal à 100 mm).

Si, comme le cas est fréquent, il existe dans l'année une période sèche où E_R est inférieur à Ep par suite de la sécheresse et une période humide où il y . drainage (voir Fig. I), la quantité d'eau drainée sera évidemment d'autant plus faible que le déficit en eau du sol aura pu atteindre des valeurs élevées. Le déficit maximum, ou réserve utile en eau du sol, est donc un facteur essentiel dans le cycle hydrologique de l'eau et le débit des cours d'eau.

Or personne ne songerait à attribuer au nombre de 100 mm retenu par Thornthwaite une valeur générale. Il est évident que cette quantité d'eau susceptible d'être extraite du sol peut varier dans des proportions importantes avec l'état de couverture et les caractéristiques physiques du sol comme nous allons tenter de le préciser maintenant.

II — Formation du mulch et déficit en eau sous sol nu

Nous avons montré (1) que si la surface du sol se trouve soumise à une évaporation E, l'humidité H (p. 100 de terre sèche) décroît à toute profondeur z proportionnellement à l'évaporation :

$$\frac{dH}{dt} = \rho(z)\, E \tag{1}$$

Ainsi la variation d'humidité Ho — H depuis l'instant initial est proportionnelle à la somme de l'évaporation $\int_o^t E dt$ (mm) :

$$Ho - H = \rho(z) \int_o^t E dt \tag{1'}$$

On a vu que ce coefficient ρ, qui exprime le taux d'assèchement à chaque niveau, décroît régulièrement avec la profondeur z.

On a montré d'autre part que ce dessèchement du sol semblait faire intervenir deux phénomènes distincts : une circulation liquide B provenant de la profondeur (jusqu'à 30 et 50 cm) et une diffusion vapeur apparente Δ qui n'assurerait en fait que le dessèchement des quelques centimètres supérieurs et qu'ainsi la valeur de ρ en surface, $\rho(o)$, était d'autant plus grande que la composante Δ était elle même plus élevée.

Sous des conditions climatiques données, l'évaporation E se maintient tout d'abord constante; le taux d'humidité en surface Hs décroît alors avec le temps selon une loi linéaire comme l'indique la relation expérimentale (1) (voir fig. II, temps 0 - 3 jours). Toutefois l'humidité en surface Hs cesse de décroître quand elle atteint une valeur He telle qu'il y ait équilibre d'hygroscopicité avec l'air ambiant. La loi (1) n'est alors plus exacte mais en même temps la couche supérieure de sol joue le rôle d'un bouchon qui s'oppose à l'évaporation. Cette dernière, dans des conditions de milieu identiques, devient alors de plus en plus faible comme le montrent les courbes expérimentales (fig. II, $t > 3$ jours).

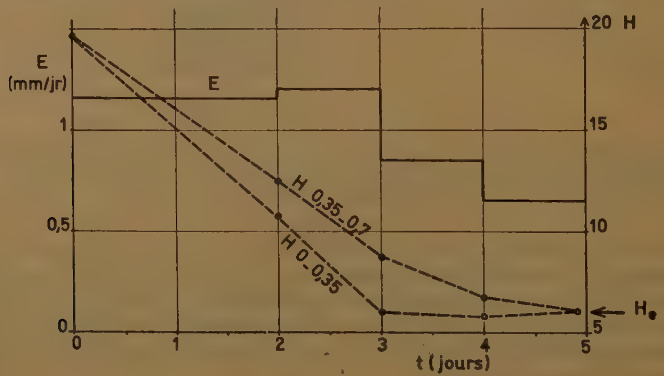


Fig. 2 — Variation de l'évaporation E et humidité superficielle en conditions invariables.

(1) Voir diffusion de l'eau à l'état vapeur et liquide au voisinage de la surface d'évaporation et dessèchement superficiels du sol — XI° Assemblée générale de l'UGGI.

Les pertes en eau qui correspondent à l'apparition de ce mulch en surface seront données par la formule :

$$\int_o^t E dt = \frac{Ho - He}{\rho(o)} \tag{2}$$

relation qui n'est en réalité qu'approximative puisqu'elle ne tient pas compte de la phase de transition où la relation (1) cesse d'être exacte et où l'équilibre n'est cependant pas encore atteint.

He dépendra du degré hygrométrique de l'air ambiant. En fait pour une terre de limon He sera définie à $\pm$ 1 près pour un degré hygrométrique allant de 40 à 90. L'humidité He relative au limon de Versailles par exemple, sera dans ces conditions de 4 à 6.

En ce qui concerne l'humidité initiale Ho, il sera particulièrement intéressant d'envisager la capacité de rétention, humidité du sol après une période pluvieuse ou une irrigation et ressuyage naturel du sol et correspondant par convention à un déficit nul. Pour le limon précité Ho est égal à 25; Ho — He est par conséquent égal à 20.

Quant au terme $\rho(o)$, l'expérience montre qu'il est susceptible de varier non seulement avec la nature du sol mais aussi avec sa structure et l'intensité d'évaporation E. Dans le cas du limon indiqué, à un degré de tassement normal ($\sigma = 1,5$) et soumis à une évaporation modérée (E inférieur à 2 mm par jour), $\rho(o)$ présente sa valeur minimum. L'expérience montre en effet que dans ces conditions l'évaporation est compensée en très grande partie par le flux liquide B de la profondeur tandis que le flux vapeur apparent qui entraîne le dessèchement de la surface est relativement faible. On a alors $\rho(o) = 0,52$ et le déficit en eau correspondant à l'apparition du mulch est :

$$\int_o^t E dt = // = \frac{20}{0,52} = 39 \text{ mm}$$

Mais on a vu que si le sol est moins tassé ou si l'évaporation E est plus grande, le débit liquide B provenant de la profondeur est relativement moins grand tandis que le débit vapeur augmente. Le coefficient $\rho(o)$ reliant le dessèchement superficiel à l'évaporation est alors plus élevé. Au maximum si E est totalement compensé par le flux vapeur apparent, le coefficient $\rho(o)$ sera (pour le limon de Versailles) de 4,5 et l'apparition du mulch correspondra au déficit :

$$\int^t E dt = // = \frac{20}{4,5} = 4,5 \text{ mm}$$

Sans doute l'évaporation se poursuit-elle quelque peu après la formation de ce bouchon superficiel. On comprend cependant pourquoi le déficit en eau ne peut dépasser sous sol nu une valeur relativement faible que la plupart des auteurs ont située entre 20 et 40 mm.

Ce freinage de l'évaporation sous l'effet du dessèchement superficiel du sol ne se produit évidemment pas si le sol est couvert par la végétation. Ici l'évaporation se situe au niveau des feuilles et les vaisseaux ligneux des tiges et des racines se comportent comme des mèches hautement conductrices qui permettent à l'eau de franchir aisément les couches desséchées de la surface. Mais de quelle façon et jusqu'à quelle limite les plantes peuvent-elles ainsi épuiser les réserves en eau du sol, c'est ce qu'il reste à examiner.

a) *Mécanisme du dessèchement*

Partant d'un grand nombre de déterminations d'humidité du sol réalisées en période de déssèchement dans le limon de Versailles, nu ou cultivé, nous avons pu mettre en évidence la loi de variation normale de l'humidité avec la profondeur z ou si l'on veut encore les formes normales des profils hydrique $H = f(z)$ au fur et à mesure du dessèchement (fig. IIIA). On notera tout d'abord, ainsi qu'il est indiqué sur la fig. IIIA que le dessèchement se poursuit beaucoup plus loin sous sol cultivé que sous sol nu. On retrouve ici cet effet de mèche du végétal qui permet à l'eau de gagner l'atmosphère lorsque la surface du sol est prise en croûte.

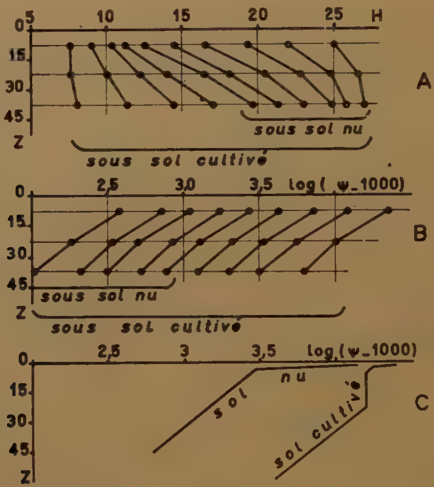


Fig. 3 — Formes normales des profils hydriques en un sol de limon.

Un fait par contre peut surprendre : pour une même humidité moyenne de l'ensemble des couches étudiées, la variation de l'humidité avec la profondeur est la même que le sol soit nu ou cultivé. On n'observe d'autre part aucune discontinuité entre les profils hydriques figurés à droite du graphique (IIIA) correspondant au sol nu ou cultivé et ceux figurés à gauche relatifs uniquement au sol cultivé. Or étant donné que le dessèchement du sol met en cause soit la succion directe dans la masse par les racines, soit la diffusion capillaire de l'eau jusqu'en surface, on aurait pu s'attendre à une répartition différente de l'humidité avec la profondeur.

Si la forme du profil est la même dans les deux cas, on est enclin à penser que le dessèchement met en cause un même phénomène physique, à savoir la diffusion capillaire par ascensum dans le sol; la succion radiculaire se ferait donc très près de la surface, immédiatement au-dessous de la croûte superficielle et créerait un appel d'eau de la profondeur conduisant alors à une variation de l'humidité identique à celle observée en sol nu.

Cette hypothèse se trouve confirmée par une seconde observation : tenant compte de la relation (potentiel capillaire ψ — taux d'humidité H) pour chaque couche de sol, on peut représenter la variation de ψ avec z. On obtient alors des courbes d'allure exponentielle, tendant asymptotiquement en profondeur vers $\psi = 1.000$.

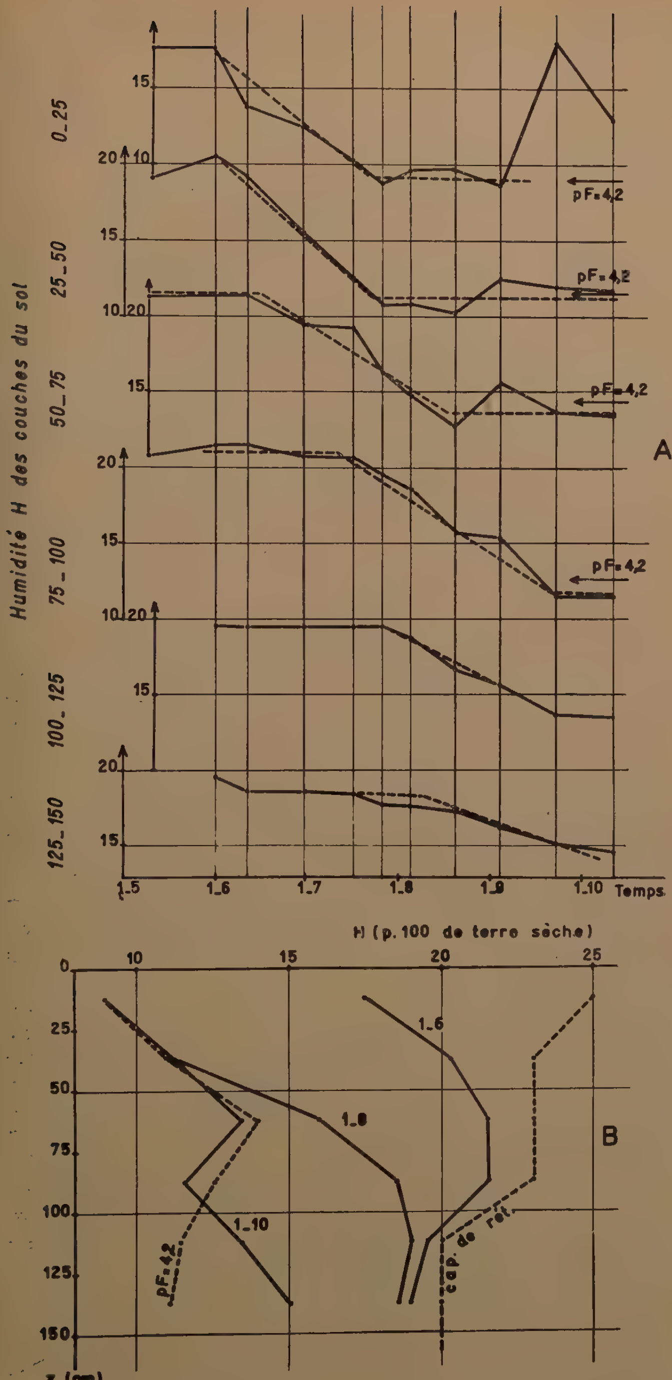


Fig. 4 — Marche du dessèchement du sol en profondeur (betterave sur limon).

Ainsi les profils log (ψ — 1.000) = $f(z)$ sont quasiment des droites qui se déduisent l'une de l'autre au fur et à mesure que le sol se dessèche par simple translation (Fig. IIIB).

Ce résultat s'applique aussi bien au sol nu qu'au sol cultivé; la seule différence est qu'en ce dernier cas, où le sol peut se déssècher davantage, les profils peuvent être beaucoup plus décalés dans le sens des log. (ψ — 1.000) élevés.

Or nous avons montré que cette variation linéaire de log. (ψ — 1.000) correspondait à un certain équilibre dans la *diffusion capillaire* per ascensum de l'eau dans le sol. Il faut dès lors situer ainsi les deux phénomènes assurant le dessèchement du sol : la succion directe par les racines dans les horizons les plus proches de la surface mais où l'eau soit cependant disponible ($pF < 4{,}2$); d'autre part une diffusion capillaire de l'eau, de la profondeur vers les horizons en question et conduisant à un profil en log. (ψ — 1.000) du même type que celui que l'on peut observer en sol nu.

On soulignera toutefois que les profils indiqués fig. IIIA et IIIB résultent d'ajustements statistiques et ne sauraient traduire que l'allure générale du dessèchement. Des déterminations d'humidité réalisées sur des tranches plus minces ont montré comment il convenait de corriger la forme linéaire des profils au voisinage de la surface et en cas de sécheresse prononcée (fig. IIIc) : En sol nu le profil présente à quelques cms de la surface une cassure, log. (ψ — 1.000) atteignant ainsi des valeurs très élevées dans les horizons superficiels. C'est le phénomène de mulch dont il a été fait mention et qui explique l'arrêt de l'évaporation. En sol cultivé, où cet effet de mulch est également observable, on constate par ailleurs qu'au delà d'une certaine profondeur où l'évaporation n'a plus d'effet, log (ψ — 1.000) ne peut excéder une certaine valeur de l'ordre de 4,2. Il s'agit on le sait du point de flétrissement permanent, humidité au-dessous de laquelle le végétal est incapable d'extraire l'eau du sol.

Des déterminations systématiques d'humidité en année particulièrement sèche ont permis d'examiner plus en détail la marche du dessèchement du sol bien au delà de l'apparition du point de flétrissement en surface. Cet assèchement gagnant progressivement la profondeur est mis en évidence sur les graphiques des fig. (IVA) donnant à titre d'exemple la variation du taux d'humidité des couches successives de terre sous une culture de betterave et fig. (IVB) exprimant les mêmes résultats sous forme de profils hydriques. La fig. (IVA) montre que lorsque l'humidité a atteint, à un niveau quelconque, le point de flétrissement permanent (correspondant à $pF = \log \psi = 4{,}2$), elle cesse alors de décroître. On retrouve ici cette limite maximum du potentiel capillaire au delà de laquelle l'eau n'est plus utilisable par les végétaux.

On constate également que le desssèchement d'une couche de terre a lieu au cours d'une période assez bien délimitée et d'autant plus reculée dans le temps que la couche en question est plus profonde.

Revenant à l'examen des profils hydriques (fig. IVB) on observe ainsi : 1°) le point de flétrissement permanent sur une certaine épaisseur 0 — h croissant avec le temps, 2°) une humidité augmentant ensuite régulièrement pour atteindre la capacité de rétention à une profondeur h' (la couche h — h' étant d'environ 50 cm d'épaisseur dans le cas présent), 3°) au-delà de h' une humidité égale à la capacité de rétention.

L'une ou l'autre des représentations portées sur les fig. IV A ou IV B montrent qu'à une profondeur donnée (couche 75 - 100 cm par exemple), le système radiculaire est absolument inactif tant que le point de flétrissement permanent n'est pas atteint à un niveau situé environ 50 cm plus haut et est au contraire susceptible, à une date ultérieure, de porter le dessèchement à son maximum ($pF = 4{,}2$).

Un tel phénomène peut s'expliquer de deux façons : d'une part il peut résulter du fait que les racines de la plante annuelle étudiée ici se développaient en profondeur au fur et à mesure que gagnait le dessèchement (voir profils radiculaires fig. V); on peut d'autre part se demander si la succion directe de l'eau par les racines n'a pas lieu de préférence dans les couches les moins profondes mais où l'eau est cependant

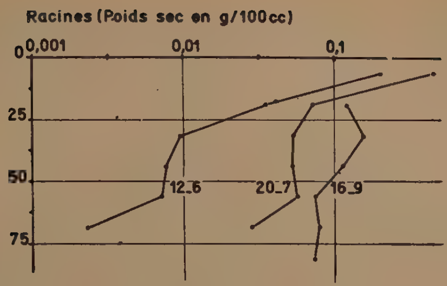


Fig. 5 — Profils radiculaires (betterave sur limon).

disponible ($pF \lesssim 4,2$). L'accroissement régulier de l'humidité du point de flétrissement permanent à la profondeur h jusqu'à la capacité de rétention à la profondeur h', similaire à ce que l'on peut observer au-dessous de la surface d'un sol nu ou cultivé (fig. III A et III B) résulterait alors d'une diffusion capillaire de l'eau jusqu'à la profondeur $h + \varepsilon$ où l'eau serait prélevée par les racines.

Les observations entreprises sur plantes perennes permettront sans doute de choisir entre ces deux hypothèses.

b) *Limite du dessèchement et déficit maximum*

Dans l'exemple précédent (fig. IV), le dessèchement du sol se poursuit jusqu'en fin de végétation et le point de flétrissement permanent atteint la profondeur de 1 m.

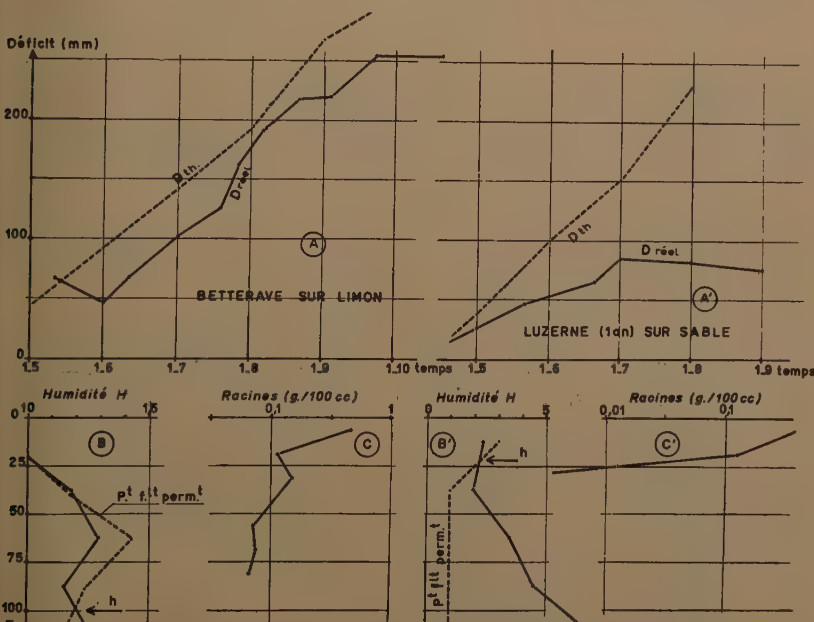


Fig. 6 — Limite du dessèchement et répartition de l'humidité et des racines en profondeur.

La fig. VI A, relative à ce même exemple, montre ainsi que le déficit en eau du sol augmente régulièrement selon une courbe à peu près parallèle à celle du déficit théorique D*th* (D*th* est la valeur qu'atteindrait le déficit en eau du sol à tout moment si l'évapotranspiration n'avait cessé d'égaler l'évapotranspiration potentielle, calculée ici d'après la formule de Thornthwaite). On notera en particulier que le déficit dépasse dans ces conditions, 250 mm.

En réalité un dessèchement aussi prononcé est tout à fait exceptionnel, tout au moins sous plantes annuelles. Il est attribuable ici à la grande extension du système radiculaire en profondeur.

En année ou en région sèche, le déficit ne dépasse généralement pas une certaine valeur Dmax, le plus souvent très inférieure aux 250 mm notés plus haut. Une fois ce déficit atteint, l'évapotranspiration, limitée aux seuls apports des précipitations, devient inférieure à l'évapotranspiration potentielle. C'est ce que l'on a pu observer notamment sous une luzerne d'un an croissant sur sable (fig. VI A').

Si l'on examine le profil hydrique H (z) correspondant à ce déficit maximum en eau du sol, on observe le point de flétrissement permanent sur une profondeur 0 — h, tandis que l'humidité croît au-delà pour tendre vers la capacité de rétention à une profondeur h'. (fig. VI B').

L'épaisseur 0 — h dépend de la profondeur du système radiculaire. Dans l'exemple mentionné ici, où h ne dépasse pas 25 cm, le taux de racines était considérablement plus faible que dans le cas de la betterave où h atteignait 1 m. ((fig. VI C et VI C').

D'autres observations nous ont permis de vérifier cette étroite corrélation entre la profondeur h d'épuisement des réserves en eau du sol et le développement des racines en profondeur; elles conduiraient en outre à fixer aux environs de 0,01 g/100 cm^3 de terre le taux minimum de racines nécessaire pour abaisser l'humidité jusqu'au point de flétrissement permanent.

L'épaisseur de terre 0 — h susceptible d'être desséchée au maximum grâce à un système radiculaire assez puissant peut varier dans des proportions importantes comme l'indiquent les quelques résultats suivants : dactyle d'un an, h = 25 cm et 50 cm. Betterave, h > 100 cm et h = 40 cm. Luzerne d'un an, h = 25 cm. Luzerne de deux ans, h > 100 cm et h = 50 cm. Trèfle de deux ans, h = 50 cm. Sous des vergers, de 5 à 10 ans seulement, on a trouvé des valeurs de h supérieures à 1,50 m. Sous couvert forestier, G. de Beaucorps a vérifié que le point de flétrissement permanent pouvait intéresser une épaisseur supérieure à 1,75 m.

L'ensemble de ces résultats permet alors un calcul simple du déficit maximum en eau du sol. Pour plus de simplicité on considérera un terrain homogène, présentant à toute profondeur la même capacité de rétention Ho, le même point de flétrissement H_1 et la même densité apparente σ. (voir fig. VII).

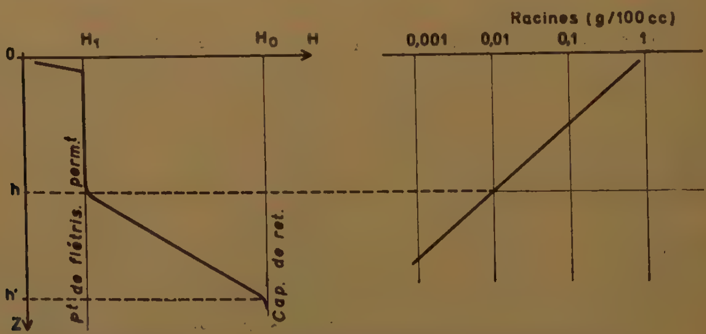


Fig. 7 — Profil hydrique limite et profil radiculaire correspondant.

Si le taux de racines excède la valeur voulue (disons, 0,01 g/100 cm³) sur la profondeur h pour que soit atteint le point de flétrissement permanent, cette même tranche est capable de céder une quantité d'eau égale, en mm, à

$$\frac{\sigma}{10}\,(Ho - H1)\,h$$

Au-dessous du niveau h l'humidité augmente pour atteindre Ho à la profondeur h' (la tranche $h - h'$ pouvant être selon nos observations de 30 à 70 cm). Si l'on assimile alors le profil hydrique à une droite, la quantité d'eau cédée par la couche $h - h'$ sera (en mm)

$$\frac{\sigma}{20}\,(Ho - H_1)\,(h' - h)$$

Explicitons les valeurs de ces deux composantes du déficit maximum en supposant une densité σ égale à 1,5 mais des valeurs différentes de $Ho - H_1$, de h et de $h' - h$.

Composantes du déficit maximum

		$Ho - H_1 =$	5	10	20
		Sol :	sableux	limoneux	argileux
I — tranche $0 - h$		$h = 20$	15	30	60
		$h = 50$	37,5	75	150
		$h = 100$	75	150	300
II tranche $h - h'$		$h' - h = 30$	11	22	44
		$h' - h = 50$	19	38	75
		$h' - h = 70$	26	52	104

La densité $\sigma = 1,5$ retenue dans ce calcul, si elle est assez commune pour les terres fines, est pratiquement un maximum. Elle peut être très inférieure, en particulier dans le cas de sol pierreux, et les valeurs du déficit maximum s'en trouveront réduites dans les mêmes proportions.

Conclusion

Les réserves en eau du sol, dont nous avons tenté de préciser la valeur, apparaissent donc extrêmement variables selon la nature du sol, l'existence ou l'absence de couvert végétal et la puissance d'enracinement de ce dernier. Si les valeurs trouvées, de quelques mm à plus de 300, encadrent de façon satisfaisante la valeur communément admise de 100 mm, celle-ci ne saurait évidemment correspondre qu'à une moyenne très générale et très grossière.

En matière d'hydrologie, il est certain que l'écoulement dans les bassins fluviaux qui, comme on l'a rappelé, dépend de cette réserve en eau, sera affecté par le type de végétation le plus commun dans l'aire géographique considérée (forêts, cultures...) et par la nature des sols et des sous-sols.

Du point de vue agronomique, l'économie de l'eau avant et peu après la période des semis consiste alors à rendre aussi minime que possible les pertes par évaporation c'est-à-dire « la réserve en eau » en l'absence de cultures. C'est à ce but que visent essentiellement la jachère et les façons culturales superficielles.

En période de pleine végétation, on doit chercher à ce que la plante dispose dans

le sol des réserves en eau nécessaires à ses besoins. Ces réserves pourront généralement être définies par l'évapotranspiration potentielle et les précipitations durant l'ensemble du cycle végétatif. Les différences d'une culture à une autre, mais sous un même climat, tiendront à ce que la période de végétation active n'est pas la même : sous le climat parisien par exemple le blé d'hiver épuise la réserve en eau d'avril à fin juin, la prairie d'avril à octobre. Le sol devra donc être choisi en conséquence.

Enfin sous des conditions climatiques et pédologiques données, la réserve dépend de la profondeur utile du système radiculaire. On a vu que ce facteur est susceptible de variations importantes. C'est par ailleurs l'unique élément sur lequel il soit sans doute possible d'agir par un choix judicieux de la variété et par une fertilisation raisonnée.

THE IMPORTANCE OF DESERT VEGETATION IN THE HYDROLOGIC CYCLE (*)

T. W. ROBINSON (**)

ABSTRACT

In regions of short supply the use of water by natural vegetation is highly competitive with man's use. Transpiration by plants forms an important part of the hydrologic cycle in these places. According to the source of their water supply the vegetation of arid regions may be divided into two general groups, xerophytes and phreatophytes. Xerophytes, which are the larger group, are plants that depend on soil moisture for their water supply, whereas phreatophytes habitually obtain their supply from ground water. Xerophytes subsist on meager amounts of soil moisture supplied by scanty rainfall, and they use much less water than phreatophytes. Utilization of soil water by xerophytes reduces the moisture content of the soil column, inhibiting downward percolation and recharge to the ground-water reservoir and thus reducing indirectly the amount of water available from the reservoir.

Draft by the phreatophytes, which have an assured supply of ground water, also reduces the amount of water available from the ground-water reservoir. As most phreatophytes are plants of low economic value and high water use, large quantities of water are wasted by transpiration into the atmosphere. Man, by reducing this waste, can make available for beneficial use a perennial supply equal to the reduction.

The use of ground water by phreatophytes varies with the species, the climate, and the quality of ground water. It is greatest where the temperature is high, the humidity low, the rainfall scanty, and the water low in mineral content.

The arid and semiarid regions of the world constitute about 35 percent of the land area. There is little precipitation in these regions, and the little that does fall is for the most part exceedingly irregular, both geographically and in time. In the habitable lands of these regions, there is keen competition between the desert vegetation and man for the use of this scant water supply. The transpiration discharge of these desert plants forms an important part of the hydrologic cycle and limits the amount of water available to man. The plants occupy a strategic position in the hydrologic cycle, and their role in it is better understood and appreciated through a knowledge of the two general classes of desert vegetation, their relation to ground water, and a comprehension of the hydrologic cycle itself. It should be borne in mind also that the climate of desert regions is favorable to a high rate of transpiration. In desert regions the inter-relationships of plants and water are perhaps more sensitive and more apparent, and may be studied more readily, than in any other climatic environment. These relationships, however, are fundamental, and when fully understood they may be applied, with modification, to other environments.

The vegetation of arid regions may be divided, on the basis of the source of their water supply, into two general classes, xerophytes and phreatophytes. Xerophytes are plants that obtain their water supply from soil moisture; phreatophytes are plants that draw on the ground water. The distinction between xerophytes and phreatophytes with respect to their sources of water supply is shown in figure 1. It is important that this distinction be kept in mind when considering the hydrology of an arid region. Xerophytes occur in desert areas where the water table is deep

(*) Publication authorized by the Director, U. S. Geological Survey.
(**) Hydraulic Engineer, Ground Water Branch, Water Resources Division, U. S. Geological Survey, Menlo Park, Calif.

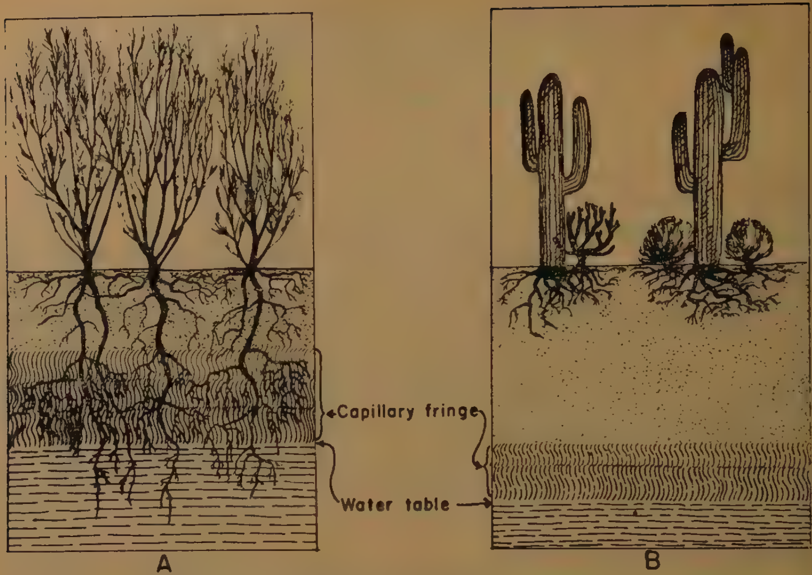


Figure 1.– Distinction between phreatophytes (A) and xerophytes (B) shown by their occurrence with respect to the water table.

and out of reach, and the plants are forced to depend upon soil moisture supplied by infrequent and irregular precipitation. As the soil moisture is generally deficient, the plants have adapted themselves to subsisting on meager amounts of water. During long dry periods they may become essentially dormant, and then after a generous rain burst into full vigor. The ability of these plants to live on small amounts of water is connoted by the term «xerophytes,» which was derived from the Greek and means «dry plant.» Cacti are excellent examples of xerophytes.

Phreatophytes are plants that habitually draw on ground water, either directly or through the capillary fringe. The term «phreatophyte» also is derived from the Greek and means «well plant.» This is a very apt description, for each phreatophyte plant may be thought of as a miniature pump, supplying its daily needs by withdrawing water from the ground-water reservoir. Phreatophytes are commonly found wherever the water table lies at shallow depth, lining the banks of streams, on flood plains, or in valley bottoms. The common willow is a typical phreatophyte.

Although the area occupied by xerophytes is much larger than the area occupied by phreatophytes, the latter have a greater effect on the water that is available for man's use.

The manner in which these two classes of plants affect the water supply of an arid region is best shown by referring to the hydrologic cycle, illustrated in figure 2. Figure 2 depicts graphically a simple hydrologic cycle—that for an undeveloped closed basin in an arid region. In the endless cycle of water movement, through the atmosphere to the land and back to the atmosphere again, water moves as a vapor and as a liquid through a maze of overland and underground routes. In part of its earthbound passage, water moves into and out of the soil-water reservoir and ground-water reservoir—the reservoirs that are the sources of water for the two classes of plants.

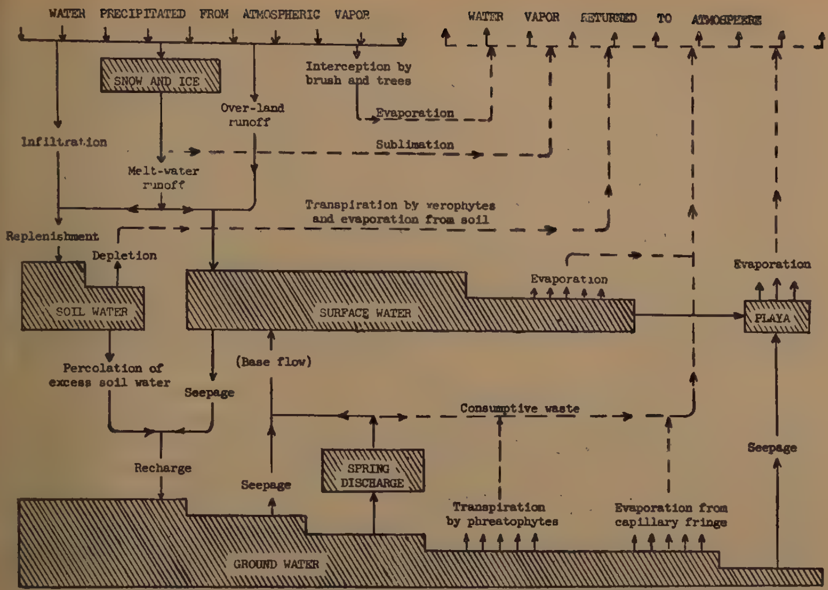


Figure 2. The hydrologic cycle for an undeveloped closed basin in an arid region. (Shaded areas represent water in storage; solid lines movement as liquid; broken lines as vapor).

The soil-water reservoir, for the most part, is replenished largely by rainfal or snowfall, and to a lesser extent by occasional overland runoff that infiltrates into the soil column. When the water that enters the soil is in excess of its moisture-holding capacity, excess water may percolate through the soil column to recharge the ground-water reservoir.

The water in the soil-water reservoir occurring as soil moisture is not directly available to man, for be cannot practically extract it from the soil in liquid form. It is available to the xerophytic plants, and it may be available to man indirectly as the products of these plants may be beneficial to him; but in this form it does not quench his thirst or meet his everyday needs. The draft by these plants depletes the soil moisture, within the depth of the root zone, and so reduces soil-water storage. This depletion is depicted graphically in figure 2 by a reduction in volume of the soil water. At the end of a prolonged dry period, the soil moisture available to the plants may be so depleted that the plants are forced to become essentially dormant. When the rains that follow a dry period are scanty the soil moisture is only partly replenished, but when they are generous then the soil moisture may be fully replenished, and at times there may even be an excess available for recharge to ground water.

Replenishment of the soil-water reservoir and eventual recharge of ground water by excess soil water is dependent upon several factors or combination of them, such as the amount and duration of individual rains, temperature, infiltration rates, and permeability and thickness of the soil column. As the result of ground-water investigations in Nevada by the U.S. Geological Survey in cooperation with the State, it was estimated that there is no significant recharge to the ground-water reservoir in southern Nevada when the annual precipitation is less than 10 inches (Maxey and Robinson, 1947, p. 16) and in northern Nevada where it is less than 8 inches (Maxey and Eakin, 1949, p. 40; Eakin, Maxey, and Robinson, 1951, p. 27).

The difference is due to temperature, evapotranspiration being greater in southern Nevada where the temperature is higher. In the Martin Creek drainage basin in the northern part of the State, a comparison of total precipitation and stream-flow showed that, on the average over a 25-year period, 9 inches of precipitation was needed to satisfy the evapotranspirative requirements of the xerophytic vegetation (Loeltz, Phoenix, and Robinson, 1949, p. 35). Some of the precipitation was disposed of by evaporation directly from the leaves, stems, and trunks of the plants and from the land surface, but the largest part was accounted for by plant transpiration.

The role of xerophytes in the hydrologic cycle is a dual one. Xerophytes have first call on the soil moisture, and these demands must be met first. The discharge through transpiration may account for most and at some times all of the annual precipitation. The other part is a consequence of the first: depletion of the soil water reservoir reduces the amount of water available for recharge to the ground-water reservoir.

Water in the ground-water reservoir, in contrast to that of the soil-water reservoir, is available to man. In the Western United States, the reservoir is recharged in part by percolation of excess soil water but largely by seepage from streams and lakes. Ground water is available to man through spring discharge or seepage to streams and lakes, or it may be obtained by him through the use of wells, tunnels, or ditches. In some localities ground water may be the only source of supply. Except where the water table is deep, this water is available to phreatophytes also, and as there is seldom enough for both, man must compete with the plants for his share. Phreatophytes, by virtue of their direct root connection with the water table, have first call on the water, with the result that the ground-water reservoir is depleted and the amount of water available to man is reduced. The depletion is manifested by lowered ground water levels and is very apparent in the reduced flow of streams. Phreatophytes, unlike xerophytes, are not forced to limit their water consumption because of an insufficient water supply, but draw freely from the ground-water reservoir to the extent of their needs throughout the growing season. In figure 2, depletion of the ground water storage by evapotranspiration is depicted by a reduction of the volume in storage. As most phreatophytes are plants of low economic value, the water consumed by them produces little that is of benefit to man. The water circulating in this segment of the hydrologic cycle is potentially available for man's use, and, by reducing nonbeneficial use, he can make available for his use a perennial supply equal to the reduction. In the arid regions of the United States, the water wasted by phreatophytes may well be one of the largest sources of reclaimable water.

In describing the water used by plant life the term «consumptive use» is generally used to denote the water evaporated or transpired from an area and is considered synonymous with the term «total evapotranspiration.» The term «consumptive use» makes no distinction as to the nature of use, but includes the water used by economic plants as well as that used by plants that have little or no economic value. In order to distinguish between these uses, the water used by vegetation of high economic value is referred to as «beneficial consumptive use,» and that for nonbeneficial vegetation, such as weeds and noxious plants, as «nonbeneficial consumptive use.» The term «consumptive waste» was suggested by Thomas (1951, p. 217) for the water used by plants that returns to the atmosphere without substantial benefit to man. (See Robinson, 1955.) It is a part of, rather than a complement to, «consumptive use.» It connotes the opposite of «beneficial use» and becomes synonymous with «nonbeneficial consumptive use.»

The water that is consumptively wasted by vegetation is available for salvage either directly or indirectly. Salvage, with respect to the consumption of water by nonbeneficial vegetation, means converting consumptive waste to beneficial con-

sumptive use. The extent to which salvage can be effected will depend upon the economics and physical conditions of each area involved.

Salvage may be accomplished in two ways: by increasing the efficiency of water consumption by plant life, and by reducing consumptive waste. In the case of xerophytes salvage may be accomplished indirectly by either method through the use of substitute vegetation —that is, by substituting plants of lesser water requirements for those of greater requirements or by replacing the low-value plants with those of higher economic value. The feasibility of this method has been demonstrated by Veihmeyer (1953, p. 201-212) in California, on a variety of test plots under different conditions of vegetative cover, rainfall patterns, topography, and soils. It was found that when the native vegetation, mostly woody brush species, was replaced by grasses and forbes or nongrasslike herbs, there was an appreciable saving of water. The moisture content of the soil at the end of the growing season was higher in the grass and forbes plots than in the undisturbed brush plots, and consequently less water was required to restore the soil to its moisture-holding capacity (field capacity), and to provide excess soil water for ground-water recharge. Not only was there a saving of water, but the water that was consumed was used beneficially, for the grasses and forbes provided forage for livestock which the woody brush species did not.

Salvage of the water consumptively wasted by phreatophytes is of greater importance than that wasted by xerophytes, for several reasons. Nearly all phreatophytes are plants of low economic value, are high users of water, and occur for the most part on the floors of valleys, on flood plains and along the banks of streams. As a result of their much higher use, the potential salvage per unit area is greater for phreatophytes than for xerophytes.

The quantity of water theoretically available for salvage in any locality is equal to the total water use by the nonbeneficial phreatophytes. It is their annual consumption per unit of area times the area of the plant growth. It has been estimated that, in the arid and semiarid regions of the western 17 of the United States (roughly the area west of the 97th degree of longitude), there are about 16 million acres of phreatophytes (Robinson, 1952, p. 60), and that they discharge about 25 million acre-feet of water into the atmosphere annually. This amount of water is equivalent to about twice the average annual flow of the Colorado River.

Salvage of water wasted by phreatophytes also may be accomplished by reducing consumptive waste or by increasing the efficiency of use. Both methods, however, require a knowledge of the occurrence and annnual consumption of ground water by the plants. Reduction of consumptive waste is accomplished by taking the water away from the plants. This may be done by lowering the ground-water level below the root zone, through pumping from wells or by drainage, and use of the salvaged water elsewhere. It may be accomplished also by preventing the water from reaching the plants, either by intercepting the ground water upgradient from the plants, and diverting it for beneficial use, or by conveying the water of streams through areas of riparian growth, through lined stream channels or pipes.

The efficiency of water consumption may be increased by replacing plants of low economic value with plants of higher value. An example of this method is provided by the Escalante Valley in Utah, where alfalfa was successfully substituted for an association of greasewood, rabbitbrush, and saltgrass (White, 1932).

Phreatophytes as consumers of ground water are becoming more and more important to the water economy of the desert and semidesert regions of the United States, and it is believed that this situation exists to some extent in all the arid regions of the world. They are important in the United States not only because of the large quantities of ground water they waste, but also because these losses occur in areas where ground water is readily available and where it can be readily put to use.

The annual rate of water consumption by phreatophytes ranges widely according to the plant species and to local conditions. Under the same conditions some species consume large quantities of water, others much less. The rate of consumption will also vary from one locality to another. The variation in the rates of use is largely dependent upon three principal factors—depth to the water table, climatic conditions, and density of growth. The use is greatest when the water table is shallow, the climate hot, and the growth dense.

The evapotranspirative discharge is greatest where the water lies at shallow depth and decreases as the depth to water increases. This has been demonstrated by tank experiments for saltgrass up to depths of 5 feet (Robinson, in press), for saltcedar and batamote up to depths of 7 feet (Gatewood, Robinson, Colby, and others, 1950, p. 137), and for cottonwood experimentally to a depth of 4.7 feet and inferentially to a depth of 12 feet (Muckel and Blaney, 1945, p. 54). In the case of saltgrass, the total use for a depth to water of 2 feet was about twice that at 4 feet. For saltcedar and batamote the use was 18 to 25 percent greater at a depth of 4 feet than at 6 feet.

The rate of use of ground water by phreatophytes is affected, to a greater or less degree, by the various elements of climate: temperature, humidity, wind movement, rainfall, lenght of growing season, and daytime hours. According to Lee (1942, p. 272), air temperature is the most influential factor in controlling the rate of transpiration. His statement was borne out, in the course of an investigation of the use of ground water by saltcedar in Safford Valley on the Gila River, Arizona (Gatewood, Robinson, Colby, and others, 1950, p. 115). It was found that the use of water closely paralleled the seasonal changes in temperatures, increasing as the air temperature increased and decreasing as it decreased. The effect of temperature was further demonstrated by the results of experiments of saltgrass grown in tanks at five locations in the western United States. The range in average air temperature during the growing season was from 54°F in the San Luis Valley of Colorado to 70°F at Carlsbad, New Mexico. For this 16°F difference in temperature, the water requirement increased 100 percent. That is, the saltgrass consumed twice as much water at 70°F as it did at 54°F.

The effect of humidity is the reverse of that of temperature. Experiments in Safford Valley showed that, as the relative humidity increased, the use of water by phreatophytes decreased, and as the relative humidity decreased the use increased (Gatewood, Robinson, Colby, and others, 1950, p. 143).

The effect of wind movement is to increase the use of water owing to the removal of the air of high humidity next to the plant leaves and replacement with air of lower humidity from adjacent desert areas.

These three elements of climate — high air temperature, low humidity, and substantial wind movement, which are characteristic of desert regions, combine to produce a potentially high transpiration rate and hence a high rate of draft on ground water. For the other elements of climate, it has been found that the use of ground water is greatest when the growing season and daytime hours are long, and the rainfall scanty.

The density of phreatophyte growth is a factor that controls the rate of water use by the plants. The water use is affected not only by the density of growth but also by the height or size of the plant, and hence the amount of foliage. These growth conditions may be described by assigning a value of 100 percent to the maximum possible growth, and zero to essentially no growth. Variations in density and size may be evaluated as a percentage in terms of areal and vertical density and expressed as a product of the two, called «volume density.» It was found in Safford Valley, Arizona (Gatewood, Robinson, Colby and others, 1950, p. 27), that the use of water

by phreatophytes is proportional to the volume and density of the foliage, being greatest where the growth is large and dense and least where it is small and scattered.

Although much has been written concerning desert vegetation, little has been done to list and classify the plants with respect to the source of their water supply. During the last 5 years the writer has assembled information and prepared a list of the plants that occur as phreatophytes in the western United States (Robinson, 195–). The list identified about 80 species of plants as phreatophytes. These plants do not belong to any one genus or family, but consist of many genera. They have only one common characteristic—that of their dependence on ground water.

Data on the annual water consumption by xerophytes is virtually nonexistent, and for phreatophytes it is scanty and has been obtained for only a few localities, all in the western United States. These data for 7 different species growing at 9 different localities are given in table 1. Information is included on the volume density and depth to the water table, when known.

TABLE 1

Annual rate of water use by some common species of phreatophytes in the western United States

Plant	Annual rate (acre-feet per acre) including precipitation	Volume density (percent)	Depth to water (feet)	Locality and remarks
Alder	5.3	—	—	Santa Ana River drainage basin, Calif.
Batamote	4.7	100	6	Safford Valley, Ariz.
Cottonwood	6.0	100	6	do
do	5.2	100	4	San Luis Rey River, Calif.
do	7.6	100	3	do
Mesquite	3.3	100	10	Safford Valley, Ariz.
Saltcedar	7.2	100	7	do
do	6.0	—	—	Pecos River, N. Mex.
Willow	4.4[1,2]	—	2	Santa Ana, Calif.
do	2.5[1]	—	1.1	Isleta, N. Mex.
Saltgrass	0.8 to 4.0[1]	—	0.5 to 5.0	

1) For plants grown in tanks.
2) Tank isolated; not in natural environment.

The importance of the role played by phreatophytes in the hydrologic cycle stands out sharply when the quantity of water they return to the atmosphere is expressed in terms of man's needs. Three-year-old cottonwoods in Safford Valley, Arizona, were found to use an average of 10.3 gallons of water a day, and saltcedar plants of the same age to use an average of 13.5 gallons a day during a 205-day growing season.

If it is assumed that the annual use, in acre-feet per acre, for the Safford Valley given in table 1—6.0 for cottonwoods and 7.2 for saltcedar—was entirely by 3-year-old plants, then the number of plants on an acre may be computed. On this basis there would be 925 cottonwoods and 850 saltcedars on an acre, or, in terms of density, one cottonwood for each 47 square feet and one saltcedar for each 51 square feet. During 1950 the average daily use by each city dweller in the United States was 145 gallons (MacKichan, 1951, p. 4). In terms of man's needs, the water used by 14 three-year-old cottonwoods or 11 saltcedars during the growing season would supply a city dweller. In terms of area, the water used by 640 acres (1 square mile) of cottonwoods or saltcedars during a growing season would supply the needs of cities of 23,500 or 28,000, respectively, for a year.

REFERENCES

Eakin, T. E., Maxey, G. B., and Robinson, T. W., 1951. Ground water in Goshute-Antelope Valley, Elko County, Nev.: Nevada State Engineer Office, *Water Resources Bull.* 12.

Gatewood, J. S., Robinson, T. W., Colby, B. R., Hem, J. D., and Halpenny, L. C., 1950. Use of water by bottom-land vegetation in lower Safford Valley, Arizona : *U. S. Geol. Survey Water Supply Paper* 1103.

Lee, C. H., 1942, Transpiration and total evaporation, *in* Meinzer, O. E. (ed), Hydrology: New York McGraw-Hill Book Co., Inc.

Loeltz, O. J., Phoenix, D. A., and Robinson, T. W., 1949. Ground water in Paradise Valley, Humboldt County, Nev.: Nevada State Engineer Office, *Water Resources Bull.* 10.

MacKichan, K. A., 1951. Estimated use of water in the United States — 1950 : *U. S. Geol. Survey Circ.* 115.

Maxey, G. B., and Eakin, T. E., 1949. Ground water in White River Valley, White Pine, Nye and Lincoln Counties, Nev.: Nevada State Engineer Office, *Water Resources Bull.* 8.

Maxey, G. B., and Robinson, T. W., 1947. Ground water in Las Vegas, Pahrump, and Indian Spring Valleys, Nev., a summary: Nevada State Engineer Office, *Water Resources Bull.* 6.

Muckel, Dean C., and Blaney, H. F., 1945, Utilization of the waters of lower San Luis Rey Valley, San Diego County, Calif.: U. S. Dept. Agriculture, Soil Conservation Service.

Robinson, T. W., 1952. Phreatophytes and their relation to water in western United States: *Am. Geophys. Union Trans.*, v. 33, no. 1.

— in press, Phreatophytes: *U. S. Geol. Survey Water-Supply Paper* 1423.

Thomas, H. E., 1951. The conservation of ground water: New York McGraw-Hill Book Co., Inc.

Veihmeyer, F. J., 1953. Use of water by native vegetation versus grasses and forbes in watersheds: *Am. Geophys. Union Trans.*, v. 34, no. 2, p. 201-212.

White, W. N., 1932. A method for estimating ground-water supplies based on discharge of plants and evaporation from soil: *U. S. Geol. Survey Water-Supply Paper* 659-A.

MONTHLY CONSUMPTIVE USE OF WATER BY IRRIGATED CROPS AND NATURAL VEGETATION

HARRY F. BLANEY **

Abstract

Monthly consumptive use (evapotranspiration) data are useful in determining the disposition of precipitation and its contribution to the ground-water supply, safe yields of ground-water basins, water yields from mountain watersheds, and irrigation requirements of crops. Results of monthly determinations of evapotranspiration and transpiration for irrigated crops may be employed to plan irrigation schedules and for estimating water requirements for each crop for maximum production. When making an inventory of the water resources of a river basin, water consumed by water-loving vegetation such as cottonwoods, saltcedar, saltgrass, and tules growing in areas of high water table and along streams become of increasing importance as greater land areas are irrigated. These plants discharge and waste large quantities of water into the atmosphere through the process of transpiration.

It is the purpose of this paper to present data on measured monthly rates of consumptive use of water for different irrigated crops and natural vegetation growing in arid and semi-arid climates of Western United States and to describe a procedure for determining monthly and daily water requirements of vegetation from climatological data for areas where monthly measurements of water use are not available.

Introduction

Consumptive use of water involves problems of water supply, both surface and underground, and watershed management, as well as those of the management and economics and multiple-purpose water projects for irrigation, power, flood control and municipal purposes. Data on monthly use of water by irrigated crops and natural vegetation are essential in planning water supply projects in arid and semi-arid regions. In this paper the term «consumptive use» is considered synonymous with the term evapotranspiration. It includes all transpiration and evaporation losses from lands on which there is growth of vegetation of any kind, whether agricultural crops or natural vegetation, plus evaporation from bare lands and from water surfaces. The rate of consumptive use depends on climate, vegetative cover, moisture supply, soils and topography.

The consumptive-use requirement for water has become an important factor in the arbitration of controversies regarding water rights in major river systems, in which the welfare of the people of valleys, cities, states and nations is involved([1],[2])*. Before the available water resources and an equitable division of the use of the waters of a river basin can be satisfactorily ascertained, careful consideration must be given to comsumptive-use requirements for water in sub-basins.

Consumptive use is the best index of irrigation requirements. Irrigation requirement is the amount of water, exclusive of precipitation, that is needed for the production of crops. It includes plant transpiration, évaporation, deep percolation, and other economically unavoidable wastes.

(*) Presented at the Eleventh General Assembly of International Union of Geodesy and Geophysics, Toronto, Canada, September 1957.

(**) Project Leader and Irrigation Engineer, Western Soil and Water Management Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Dept. of Agriculture, Los Angeles, California.

(*) Figures in parenthesis refer to literature cited at end of paper.

A large part of the irrigation water applied to farm land is consumed by evaporation and transpiration. In field measurements it is hard to separate evaporation from transpiration and the two processes are usually considered as one and called evapotranspiration or comsumptive use.

Actual measurements of consumptive use under each of the physical and climatic conditions of any large area are expensive and time consuming. The results of research and measurements of the consumptive use of water, along with meteorological observations, provide basic data required for estimating water requirements for irrigated lands where few or no data, except climatological, are available.

Early studies in united states

Research studies have been made on evaporation from soil and evapotranspiration by federal, state, and other agencies at various times since 1900. One of the first studies of evapotranspiration by irrigated crops was made in Southern California in 1903 by the Irrigation Investigations Section of the Office of Experiment Stations, United States Department of Agriculture. At various times since that date this agency, now known as the Soil and Water Conservation Research Division, has studied and measured consumptive use by different agricultural crops and natural vegetation in many sections of the Western United States, in cooperation with state agricultural experiment stations, state engineers, and other agencies. Usually evaporation, temperature, humidity, precipitation, and wind movement were recorded at the same time. Thus, data are available for correlating consumptive use measurements with evaporation, temperature, and other climatological observations.

Both evaporation from water surfaces and consumptive use by vegetative growth respond freely to changes in temperature, humidity, and wind movement. Thus evaporation from United States Weather Bureau pans may be used as an index of rates of consumptive use for areas in which there is ample moisture for consumptive water requirements. The writer first became interested in the correlation of pan evaporation, meteorological observations and evapotranspiration measurements in 1919, while in charge of research studies at the United States Department of Agriculture Irrigation Field Laboratory at Denver, Colorado ([3]). These studies included observations of temperature, humidity, and wind movement, along with measurements of evaporation from pans ranging from one to 12 feet in diameter, evaporation from soil tanks and consumptive use of water by irrigated fields crops grown in lysimeters.

Measurements of monthly rates of water use

Methods used to measure consumptive use of water by irrigated crops and natural vegetation under field conditions were described by the author ([4]) at the Tenth General Assembly of IUGG in Rome in September 1954. The source of water used, whether from irrigation, precipitation, or ground water is a factor in selecting a method. The methods usually employed in hydrologic and engineering studies in Western United States to determine monthly rates of use are: soil-moisture depletion studies on plots; tank or lysimeter measurements; and empirical formulae. Soil moisture depletion studies and lysimeters have been used for many years to measure rates of water consumption by irrigated crops and natural vegetation in Western states.

In recent years the soil-moisture depletion method usually has been employed to measure the use of water by agricultural crops growing in field plots. The change in moisture content of the soil within the root zone is measured from soil samples taken with a soil tube before and after irrigation at one-foot sections to depths of 3 to 12 feet depending on the depth of crop roots. Figure 1 shows a set of soil sampling equipment consisting of a compressed-air unit, soil-tube jack, hand hammer and soil-sampling tube which have been employed in consumptive use, irrigation and rainfall penetration studies in Southern California. Usually samples of soil mulch are taken separately for determining the evaporation loss after irrigation. Standard laboratory practices are used to determine the quantity of water removed from the soil by evaporation and transpiration ([5]).

At various times during the past 30 years, the writer has employed this method and the results have been satisfactory ([6,4]). Table 1 illustrates how the results of soil-moisture depletion studies are tabulated to show transpiration of water in one-foot sections to depth of root zone. Results of some measured monthly transpiration by irrigated crops in Arizona and California are shown in Table 2. Consumptive use for the irrigation season can be estimated by adding about 5 inches of evaporation to the total transpiration. Table 3 gives results of some measurements of monthly consumptive use of water during the irrigation season in Western United States by various investigators.

TABLE 1

*An Example of Measurements of Monthly Transpiration in One-foot Sections to a Depth of Five Feet by Lemon Trees Growing in Fine Sandy Loam, San Fernando Valley, Los Angeles, California **

Period	Number of days	*Soil moisture* 1st foot	*loss, acre-inches* 2nd foot	*per acre* 3rd foot	*inches* 4th foot	5th foot	Total	Loss per 30 days
Mar. 8 — Mar 28	21	0.69	0.22	0.20	0.10	0.00	1.21	2.03
Mar. 29 — Apr. 10	13	0.63	0.12	0.16	0.16	0.00	1.07	2.46
Apr. 11 — May 1	21	0.60	0.20	0.20	0.19	0.00	1.19	1.70
May 2 — June 5	36	1.06	0.66	0.43	0.38	0.12	2.65	2.21
June 6 — June 21	16	1.04	0.48	0.39	0.18	0.09	2.18	4.08
June 22 — July 20	29	0.85	0.41	0.42	0.37	0.23	2.28	2.36
July 21 — Aug. 23	34	1.41	1.00	0.97	0.58	0.55	4.51	3.99
Aug. 24 — Oct. 3	41	1.75	1.38	0.58	0.58	0.50	4.79	3.51
Oct. 4 — Oct. 31	28	0.80	0.44	0.56	0.45	0.09	2.34	2.51
Nov. 1 — Nov. 14	14	0.74	0.22	0.03	0.18	0.01	1.18	2.53
Nov. 15 — Dec. 6	22	0.37	0.42	0.24	0.23	0.27	1.53	2.08
Total	275	9.94	5.55	4.18	3.40	1.86	24.93	
Percent of total use		40	22	17	14	7	100	

Evaporation loss from mulch ≐ 4.8 inches (furrow irrigation)

Consumptive use = evaporation + transpiration

= 4.8 + 24.9 = 29.7 acre-inches per acre (inches)

* Measurements made by Harry F. Blaney in cooperation with Arnold Lane of the Los Angeles City Department of Water and Power.

TABLE 2

Examples of measured monthly transpiration by irrigated crops in Arizona and California determined by Soil-Moisture depletion method. Compiled by Harry F. Blaney.

Location	Crop	*Transpiration, depth in inches* Apr.	May	June	July	Aug.	Sept.	Oct.	Total	Authority
ARIZONA										
Phoenix	Oranges	2.5	3.3	3.9	4.4	4.2	3.8	2.6	24.70	Harris
»	Grapefruit	3.3	4.1	4.9	5.6	5.7	4.9	3.4	31.9	»
Mesa	Alfalfa *a*	5.0	6.5	9.0	12.0	—	3.0	4.0	39.5	»
Tempe	Dates	2.3	3.4	4.5	5.0	5.6	5.4	4.9	31.1	»
Mesa	Cotton	1.1	1.6	3.5	6.8	7.0	6.0	5.0	31.0	»
»	Hegari			—	2.6	4.6	6.0	5.9	19.1	»
»	Guar			—	2.0	6.0	5.0	3.0	16.0	»
»	Soybeans			2.2	4.2	6.3	4.5	2.8	20.0	»
»	Sorghum			—	2.4	8.3	7.3	2.4	20.4	»
CALIFORNIA										
Riverside	Oranges	2.6	3.0	3.6	4.4	4.4	3.1	2.7	23.8	Pillsbury
»	»	2.0	3.1	4.0	4.0	3.2	3.1	3.0	22.4	»
Corona	Lemons	1.8	2.6	2.7	2.9	3.0	3.2	2.6	18.8	»
»	Oranges	2.0	2.2	3.4	4.4	3.2	2.6	2.4	20.2	»
Tustin	Oranges *b*	1.3	1.9	2.7	3.1	2.9	2.4	1.7	16.0	»
Anaheim	Oranges *b*	1.3	2.3	3.5	3.5	2.9	2.2	1.8	17.6	»
Azusa	Oranges *b*	1.7	2.2	2.8	3.3	3.2	1.9	2.2	17.3	Blaney
Los Angeles	Lemons	1.9	2.6	2.5	3.3	3.3	3.2	2.8	19.6	»
» »	Lemons	1.9	2.0	2.7	3.4	3.1	3.1	2.4	18.6	»
San Bernardino	Grapefruit	2.4	3.1	3.7	4.2	4.0	3.4	2.8	23.6	Pillsbury
Escondido	Lemons *b*	1.3	1.4	1.8	2.5	2.6	2.6	2.0	14.2	Blaney
Los Angeles	Walnuts	3.8	4.5	5.2	5.4	4.3	2.1	1.3	26.6	»
Tustin	Walnuts	1.0	4.0	3.2	6.3	5.2	3.6	1.6	24.9	Beckett
»	Walnuts	1.0	4.1	4.5	6.4	5.5	2.9	1.8	26.2	»
Santa Ana	Oranges *b,c*	1.4	1.9	2.5	2.9	2.8	2.4	1.7	15.5	»
» »	» *b,d*	1.2	1.5	1.7	1.7	1.8	1.6	1.3	10.8	»
Shafter	Cotton	0.2	1.0	3.2	7.7	8.9	5.5	3.0	29.5	»
»	Cotton	0.3	1.1	2.3	4.6	6.7	5.4	3.6	24.0	»

a Evapotranspiration
b Coastal climate
c Old trees
d Young trees

TABLE 3

Examples of measured monthly consumptive use (evapotranspiration) by irrigated crops during irrigation season in Western United States (Compiled by Harry F. Blaney.)

Location	Crop	Consumptive use (evapotranspiration), Inches April	May	June	Juli	Aug.	Sept.	Oct.	Total:	Authority
CALIFORNIA										
Los Angeles	*a* Lemons	2.1	2.6	3.3	3.9	3.7	3.4	2.8	21.8	Blaney
» »	*a* Oranges	2.2	2.2	3.1	3.4	3.7	3.1	2.9	20.6	»
» »	*a* Walnuts	3.8	5.0	5.9	6.1	5.0	2.8	2.0	30.6	»
» »	*a* Alfalfa	3.3	6.7	5.4	7.8	4.2	5.6	4.4	37.4	»
Ontario	Peaches	1.0	3.5	6.7	8.0	6.5	2.7	1.4	29.8	»
Shafter	Cotton	.5	1.0	4.0	8.5	9.7	5.8	3.2	32.7	Beckett
Firebaugh	Cotton	—	.8	1.1	7.3	7.8	3.6	2.0	22.6	Adams
Firebaugh	Cotton	—	.4	.7	8.4	9.5	3.0	2.5	24.5	»
Delta *b*	Alfalfa	3.6	4.8	6.0	7.8	6.6	6.0	1.2	36.0	Mathew
» *b*	Potatoes	—	1.8	4.6	6.2	3.6	1.8	—	18.0	»
» *b*	Truck	1.2	3.0	6.0	5.4	5.4	3.6	1.8	26.4	»
» *b*	Sugar Beets	1.6	3.8	6.1	7.3	6.4	2.4	—	27.6	»
» *b*	Beans	1.9	2.4	1.7	2.9	6.9	4.4	—	20.2	»
» *b*	Fruit	2.2	3.8	6.0	6.8	4.8	2.8	.8	27.2	»
» *b*	Onions	1.6	3.2	5.9	5.2	2.4	1.9	—	19.8	»
Davis	Sugar Beets	—	5.2	5.7	7.1	5.8	—	—	23.8	Veihmeyer
»	Tomatoes	—	—	3.2	6.2	4.9	4.7	—	22.3	»
»	Alfalfa	—	6.8	7.9	8.3	7.1	4.3	—	—	»
»	Prunes	—	5.8	6.0	7.6	6.5	5.0	—	—	»
»	Peaches	—	5.4	6.4	7.9	7.2	5.0	—	—	»
»	Walnuts	—	6.6	6.7	8.4	7.2	4.8	—	—	»
»	Grapes	—	4.6	4.9	6.2	5.3	4.3	—	—	»
Winters	Apricots	—	—	5.6	6.8	6.5	4.9	—	—	»
NEBRASSA										
Scottsbluff	Alfalfa	1.4	4.0	7.0	7.1	6.4	3.0	—	28.9	Bowen
»	Beets	1.9	3.3	5.2	6.9	5.8	1.1	—	24.2	»
»	Potatoes	—	—	—	3.4	5.8	4.4	—	—	»
»	Oats	—	3.0	6.1	5.1	—	—	—	14.2	»

a In San Fernando Valley, City of Los Angeles, California
b In Sacramento-San Joaquin Delta, California

Measurements of consumptive use of water by natural vegetation have been made by various methods. Vegetative types, ranging from grasses to treees, have been studied, but owing to the inherent differences in aerial and root growth, different methods of approach are necessary. The source of water consumed by the vege-

TABLE 4

Examples of measured monthly consumptive use of water by natural vegetation growing in lysimeters with ghih-watertable in Western United States
(Compiled by Harry F. Blaney)

Location	Type of vegetation	April	May	June	July	Aug.	Sept.	Oct.	Aut orj
		Consumptive use evapotranspiration., inches							
CALIFORNIA									
Bonsall	Cottonwood *a*	5.2	8.5	7.5	9.6	9.4	7.2	—	Muckel
»	» »	7.0	10.5	11.9	16.5	14.2	9.8	—	and Blaney
» *c*	Tules	4.6	7.1	7.5	8.6	7.4	5.7	4.7	Ditto
Victorville *d*	Tules	7.5	11.6	12.2	14.6	12.0	10.6	5.7	»
Santa Ana	Saltgrass *b*	3.6	3.7	5.8	7.6	6.1	4.5	3.0	Blaney and
» »	» *e*	.7	.7	1.3	2.7	3.1	1.8	1.7	Young
» »	Willows	2.3	3.5	3.8	4.2	4.8	4.2	2.9	Ditto
» »	Wire rush *f*	7.8	8.6	10.3	13.7	12.7	10.7	8.2	»
San Bernadino	Bermuda grass *a*	2.0	2.1	4.5	5.4	3.9	3.1	.9	»
» »	» » *q*	2.0	2.1	4.5	5.4	3.9	3.1	.9	»
» »	Tules	5.4	4.6	6.0	6.8	5.8	5.1	4.9	»
COLORADO									
Alamosa	Tules	—	—	11.4	11.6	8.3	4.1	2.0	Blaney
»	Meadow Grass	—	—	6.5	8.3	7.8	5.8	1.2	»
Garnett	Saltgrass *e*	1.7	3.0	6.2	6.7	5.9	3.5	1.6	»
NEW MEXICO									
Albuquerque *h*	Tules	5.2	5.3	10.7	13.1	10.7	7.8	2.8	Elder
h *h*	Saltgrass *g*	.1	.6	2.8	3.5	4.2	3.4	1.2	»
Isleta	» *i*	.6	4.8	5.5	6.1	5.6	3.8	.8	Blaney
»	Sedge *j*	6.5	10.5	12.4	16.2	11.7	7.5	5.6	»
»	Willows *k*	2.3	3.5	4.2	6.1	5.6	3.8	1.8	»
Mesilla	Saltgrass *l*	2.0	2.1	3.8	9.2	7.9	6.1	4.1	»
Carlsbad	Saltgrass *g*	3.2	4.7	7.2	11.8	9.2	7.6	4.3	»
»	Sacaton *g*	4.5	6.4	5.8	8.1	7.1	6.1	3.5	»
»	Saltcedar *g*	—	—	3.3	4.8	8.4	8.6	6.8	»
»	Saltcedar *b*	—	—	1.9	4.3	8.2	6.1	6.1	»
»	Sacaton *b*	3.1	2.7	6.6	6.7	7.8	5.7	3.8	»

a Water-table 36 ins.
b Water-table 48 ins.
c Coastal area
d Mojave Desert
e Water-table 12 ins.
f Isolated tank
g Water-table 24 ins.
h At Los Griego Station
i Isleta Station
j Growing in water
k Water-table 9 to 18 ins.
l Water-table 14 ins.

tation wheter from a high water table or from rainfall and soil moisture, if is an additional factor influencing the selection. The principal methods used are: (a) by lysimeters or tanks and (b) soil-moisture depletion studies (4). Both methods have been used by the writer in California, Colorado and New Mexico ([1],[2],[7]).

The natural vegetation most often grown in lysimeters or tanks is of two classes: plants which grow with their roots in water, and those which use capillary moisture. The results of some measurements of monthly rates of water used by natural vegetation, growing in lysimeters or tanks with water-table, are shown in Tqble 4.

Measurements of use of water by soil-moisture studies are generally conducted in areas where the water table is some distance below the root zone. The amount of precipitation retained in the soil is measured by means of soil samples taken from definite depths before and after each rainstorm. Data on monthly consumptive use determined by this method are rather limited. In semi-arid regions a large portion of moisture from precipitation is held within the root zone where it is available for use by plants. This is the situation in Santa Ana Valley of Southern California where most of the rainfall occurs during the period October to March. The results of a three years study in this area by Blaney and Taylor ([7]) shows: (a) that a seasonal rainfall of less than 19 inches is usually consumed by the brush covered land before there is any contribution to the ground water. The monthly use of water ranged from 1.0 inch in December to 3.3 inches in March with an average monthly rate of 2.4 inches for brush during the period October to June and (b) when the soil supports a dense grass and weed cover, the consumptive use ranges from 12 to 15 inches before deep penetration takes place. The average rate of use during the period December to April was 2.1 inches per month.

Determining water use from climatic data

For many years irrigation engineers have used temperature data in estimating annual consumptive use of water in areas of Western United States ([1,2]). In 1924 Hedke developed the effective heat method on the Rio Grande ([1]). By this method consumptive use is estimated from an analysis of the heat units available to the crops of a particular valley. It assumes that there is a linear relation between the amount of water consumed and the quantity of heat available. This method and others were usually confined to estimating annual or seasonal use of water rather than monthly consumption.

In 1940 Blaney and Morin of the U. S. Department of Agriculture, in connection with the Pecos River Joint Investigation ([2,8]), developed an empirical formula for computing monthly rates of evaporation and evapotranspiration from mean monthly temperature, daytime, hours, and humidity records. Later, because humidity records were not readily available, Blaney and Criddle ([9]) simplified the Blaney and Morin formula by eliminating humidity. This method has been used by Federal and State agencies in United States and by other countries to compute irrigation requirements for crops growing in arid and semi-arid areas throughout the World.

Actual measurements of consumptive use under each of the various physical and climatic conditions of any large area are expensive and time consuming. The Blaney-Criddle method provides a rapid method of transferring the results of careful measurements of evapotranspiration made in several areas to other areas tof similar climate. Briefly, the procedure is to correlate existing measured monthly consumptive-use data with monthly temperature, percent of daytime hours, precipitation, growing period, or irrigation season. Coefficients so developed for different crops are used to transpose consumptive-use data for a given area to other areas for which only climatological data are available. Expressed mathematically, $U = KF = \Sigma kf$ where

U = Consumptive use (evapotranspiration) in inches for any period.
F = Sum of monthly use (f) factors for the period (sum of the products of mean monthly temperature (t) and monthly percent of annual daytime hours (p).
K = Empirical coefficient (irrigation season or growing period).
t = Mean monthly temperature in degrees Fahrenheit.
p = Monthly percent of daytime hours of the year.
f $= \frac{t \times p}{100} =$ monthly use factor.
k = Monthly use coefficient.
u $= kf =$ monthly consumptive use in inches.

TABLE 5

Examples of monthly consumptive use coefficients (k) for irrigated crops based on field measurements of evapotranspiration and temperatures

Location	Crop	*Mounthly coefficients* (k) *a* Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
ARIZONA										
Mesa	Alfalfa	0.74	0.84	0.91	1.10	1.30	—	0.90	0.75	0.75
Mesa	Cotton	—	.30	.40	.60	.80	.80	.70	.60	—
Mesa	Soy beans	—	—	—	.35	.60	.90	.80	.50	—
Mesa	Guar	—	—	—	—	.30	.80	.90	.55	—
Phoenix	Grapefruit	.55	.65	.65	.70	.70	.75	.75	.70	.65
Phoenix	Oranges	.53	.56	.56	.58	.58	.61	.61	.61	.60
CALIFORNIA										
Coastal	Alfalfa *b*	.60	.65	.70	.80	.85	.85	.80	.70	.60
Intermediate	» *c*	.60	.70	.75	.80	.95	.95	.80	.75	.70
Interior	» *d*	.65	.70	.80	.90	1.10	1.00	.85	.80	.70
Davis	»	—	.70	.80	.90	1.10	1.00	.80	.70	—
San Joaquin Delta	Alfalfa	—	.70	.75	.85	1.00	1.00	.90	.80	—
San Fernando	»	—	.70	.80	.80	.90	.90	.90	.80	.70
Orange County	Oranges *b*	—	.40	.40	.50	.55	.50	.54	.40	.40
Los Angeles Co.	» *c*	—	.40	.40	.55	.55	.55	.55	.55	.50
» » »	Lemons *c*	—	.40	.40	.50	.50	.55	.60	.50	.40
Riverside	Oranges *d*	—	.50	.50	.55	.60	.60	.60	.60	.50
San Joaquin Delta	Beets	—	.30	.60	.85	.95	.90	.40	—	—
Davis	Beets	—	—	.80	.80	.95	.80	—	—	—
Davis	Tomatoes	—	—	—	.45	.80	.70	.80	.70	—

a $k = \frac{u}{f} = \frac{\text{consumptive use}}{\text{use factor}} =$ monthly coefficient
b Coastal climate
c Intermediate climate
d Interior area

Computations of (K) from observed data for normal water supplies and growing seasons gave values for irrigated corps in arid and semi-arid areas as follows: alfalfa 0,85; corn 0.80; cotton 0.65; grass hay and pasture 0.75; citrus treees 0.50 to 0.65; deciduous trees 0.60 to 0.70; potatoes 0.75; rice 1.10, and vegetables 0.60 to 0.70. Values of (K) for natural vegetation having ample moisture available from ground water are as follows: very dense 1.30; dense 1.20; medium 1.00, and light 0.80.

In order to design irrigation systems for peak use of water, there is a need for monthly coefficients (k) in equation $u = kf =$ monthly evapotranspiration in inches. Very little information has been published on this subject. For some crops like citrus, the monthly coefficients are more or less uniform throughout the irrigation season. On the other hand, the monthly coefficients for alfalfa may range from 0.65 in April for coastal areas to 1.10 in July for arid areas. Table 5 presents some values of (k) for crops having an adequate irrigation water supply.

LITERATURES CITED

(1) Water Utilization, Upper Rio Grande Basin, by Harry F. Blaney, Paul A. Ewing, O. W. Israelsen, Carl Rohwer, and F. C. Scobey. National Resources Committee, Part III. Fberuary 1938.

(2) Consumptive Water use and Requirements, by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle. Report of the Participating Agencies, Pecos River Joint Investigation. National Resources Planning Board. June 1942.

(3) Progress Report on Evaporation and Consumptive use of Water Studies at Denver Irrigation Field Laboratory, Colorado, by Harry F. Blaney, Division of Irrigation, U. S. Dept. of Agriculture. 1920. (Typed).

(4) Evapo-Transpiration Measurements in Western United States, by Harry F. Blaney, Division of Irrigation and Water Conservation, U. S. Dept. of Agriculture. Publication no. 38 de l'Association Internationale d'Hydrologie (Assemblee générale de Rome, tome III).

(5) Irrigation Water Requirement Studies of Citrus and Avocado Trees in San Diego County, California, 1926 and 1927, by S. H. Beckett, Harry F. Blaney, and C. A. Taylor, Univ. of Calif., College of Agriculture, *Agr. Expt. Sta. Bul.* 489. 1930.

(6) Progress Report on Cooperative Research Studies on Water Utilization, San Fernando Valley, California, Irrigation Season of 1940, by Harry F. Blaney, and Homer J. Stockwell, Jr. Division of Irrigation, U. S. Dept. of Agriculture. June 1941. (Typed).

(7) Rainfall Penetration and Consumptive use of Water in Santa Ana River Valley and Coastal Plain, by Harry F. Blaney, C. A. Taylor, and A. A. Young. *Calif. State Bulletin* No. 33, Dept. Public Works, Div. Water Resources. 1930.

(8) Evaporation and Consumptive use of Water Empirical Formulae, by Harry F. Blaney, and Karl V. Morin, Part I, *Transactions Amer. Geo. Union.* 1942.

(9) Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data, by Harry F. Blaney, and Wayne D. Criddle, Division of Irrigation and Water Conservation, U. S. Dept. of Agriculture. SCS TP-96, August 1950.

SYMPOSIUM SUR LA ROSÉE ET LES CONDENSATIONS OCCULTES

TORONTO 12 SEPTEMBER 1957

Présents :

G. Tison, Belgium; Harry Blancy, U.S.A.; Thomar w Robinson, U.S.A D. D. Smith, U.S.A.; L. L. Harrold, U.S.A.; A. Volker, Holland; H. Kuron, Germany; H. Kohnke, U.S.A.; L. B. Mac Hattie, Canada; Leo-W. Robertson, Canada; J. Rodier, France; M. Pardé, France; F. Fournier, France; Th. Thijsse, Netherlands; J. Tixeront, Tunisie; J. Lambor, Poland; B. Guilmet, France; L. Serra, France; E. L. Hamilton, U.S.A.; P. O. Wolf, U.K.; R. N. Wilson, U.S.A. Y. Abdel Magered, Sudan; E. Ben Osman, Tunisia; Schoeller, H., France; R. K. Linsley, U.S.A.; M. A. Kohler, U.S.A.; W. Friedrich, Germany; L. Gherardelli, Italy; R. G. Barry, Canada; M. Goldschmidt, Israel; L. J. Tison, A.I.H.S.

Certaines des contributions ne donnent pas lieu à interventions du fait qu'elles sont simplement résumées par des compatriotes des auteurs qui n'ont pu se permettre le déplacement à Toronto.

D'autres ne sont présentées que par titre.

L'étude de M. Damagnez donne lieu à l'intervention suivante de M. Schoeller :

L'augmentation de l'humidité ne se faisant que dans les 5 cm supérieurs du sol, la condensation ne doit pas alors contribuer à l'alimentation directe de la nappe. Cependant, cette condensation diminue la part d'évapotranspiration à retrancher de la pluviométrie. Elle intervient à ce titre dans le bilan hydrologique. Ces observations ne se réfèrent q'au cas présenté.

Dans le même ordre d'idées, M. Rodier observe qu'on a remarqué sur certains petits cours d'eau des variations diurnes de débits qui s'expliquent peut-être par l'action de la rosée. L'évaporation dans la matinée de l'humidité condensée à la fin de la nuit « protège » le bassin, le matin, diminuant les pertes.

Au sujet de la communication de MM. Harold et Dreibellis, M. Schoeller attire l'attention sur l'importance de la condensation annuelle : 250 à 300 mm. La condensation intervient dans le bilan hydrologique considéré dans ses détails. Elle doit jouer un rôle dans la quantité d'eau infiltrée jusqu'à la nappe, par suite de la diminution du déficit de saturation de la partie supérieure du sol et de la demande moindre de la végétation à la pluie.

Mr. Harrold: This comment is appreciated.

Remarque de M. Serra à la suite de l'intervention de M. Schoeller; Il est évident que les totaux de rosée trouvés théoriquement et expérimentalement sont très importants. Mais ils n'affectent que la couche superficielle du sol (quelques centimètres) et n'ont sans doute pas à être pris en considération dans le bilan hydrologique qui est un cycle fermé. Donc grande importance pour les pédologues et les agronomes, mais moins peut-être pour les hydrologues. D'ailleurs dans les termes « Evaporation et Evapotranspiration » du bilan, il en est tenu plus ou moins compte (c'est le total évaporation plus rosée).

Answer of Mr. Harrold: In the general term «evapotranspiration», the normal usage includes the condensation plus the absorption of water «dew». Actually the daily depletion of soil moisture by evapotranspiration is made up of moisture loss (evapotranspiration) and moisture gain (dew). It is important in the science of hydrology to recognize and evaluate these two different phenomena.

Mr. Goldschmidt. 1) Does condensation take place in the soil or is it the dew formed on the surface which penetrates into the soil?

2) Are the interstices of the soil sufficiently replenished to enable an increase of the moisture by quantity?

3) Has condensation in soil, or repenetration of dew in the soil, been observed in other parts of the world?

Answer of Mr. Harrold:

1) Dew condensation in the soil below two inches is very small because of only small temperature fluctuations in the day. Most of dew is from atmosphere above the soil.

2) Soil moisture increase from the dew itself has not been enough to reach saturation and subsequently increase percolation. It is possible that in (over) areas of heavy dew, percolation from absorbed precipitation would occur sooner and total more than that in areas of low dew.

3) I have no personal knowledge of the value of the dew in many parts of the world. The literature indicates that dew is of recognized value in many different areas.

Question of Mr. Volker:

Could you tell something about the variation of the percolation rate in the course of the year?

Mr. Harrold: Percolation from the bottom of the 8-feet deep lysimeter has occurred mostly in the season of high soil-moisture. About 80 % of the annual percolation in Ohio U.S.A. is in four months: February-May. Evapotranspiration in May-August usually depletes soil moisture to such an extent that percolation stops from July to December.

Mr. L. B. Mac Hattie

This paper is very interesting because it shows how large dew can be in comparison with rainfall. The question arrises: How representative of large areas are these dew measurements? In this connection, could the topographic surroundings of the lysimeters be described, and proximity to any sources of moisture e.g. bodies of water mentioned?

Answer:

These lysimeters are located on sloping ground at an elevation of about 1200 ft m.s.l. Valley bottoms are at 800 ft. m.s.l. and hill tops at elevation of near 1300 ft. Major source of atmospheric moisture is Gulf of Mexico, nearly 2000 miles

away. Valley bottoms near the lysimeters have a greater range in daily air temperature fluctuations than that at the lysimeter site. Dew in these spots is likely to be larger than that measured by the lysimeters.

La communication de MM. Visentini et Vanni donne lieu à une intervention de M. Pardé :

Il demande si M. Gherardelli qui a présenté cette communication a suivi de près les observations et calculs faits par M. Visentini sur bilan précipitations-écoulement du Fradolfa (haut bassin de l'Adda), il y a plus de 20 ans. M. Visentini concluait à des précipitations occultes considérables d'après les relevés de précipitations à des totalisateurs situés sur le glacier dei Farni, à des altitudes peut-être trop basses, selon M. Pardé, pour représenter les véritables précipitations moyennes sur le petit bassin en question.

M. Gherardelli avoue qu'une variabilité des précipitations d'un endroit à l'autre, en montagne, est à craindre, comme le dit M. Pardé, mais il faut bien dire que les postes d'observation, sur les bassins glaciers, sont difficiles à installer et difficiles à observer. Il faut se contenter de ce qu'on a. D'autre part, un réseau d'observations existe, bien qu'il ne soit pas aussi serré qu'on le désirerait et les bassins des glaciers du versant méridionnal des Alpes sont très petits (de l'ordre de la dizaine de Km^2).

DEW MEASUREMENT BY THERMODYNAMICAL MEANS

GUSTAV HOFMANN

Meteorological Institute of the University of Munich

ABSTRACT:

Since the heat released in the condensation of dew influences the temperature of a body it is possible to measure dew rate on an artificial dew collector by measuring its temperature. The design of an apparatus working on this principle is described. Dew measurements made in a night with varying cloud cover show the influence of nocturnal net radiation on the dewfall. By means of a thermodynamic dew formula the effects of different meteorological factors on dew formation are outlined.

The heat balance and therefore the temperature of a freely exposed blackened metallic plate is influenced at night by the radiation, the ventilation, the air temperature and also by the rate of dew formation. Assuming stationary conditions, we can write

$$S + L + V = 0 \tag{1}$$

Where S is the net radiation, L the heat transport to the surface, and V the heat set free by the condensation of dew. All values in (1) are positive, if energy is directed toward the surface of the plate, and can be given in mcal cm^{-2} min^{-1}. Setting for

$$S = S_L - \alpha'_s (\delta_1 - \delta_L) \qquad L = -\alpha_L (\delta_1 - \delta_L), \tag{2, 3}$$

where S_L is the net radiation of the same surface at δ_L, δ_1 the temperature of the surface, δ_L the air temperature, α_S the radiation transfer coefficient ($4\sigma T^3$) and α_L the heat transfer coefficient, we get

$$S_L - (\alpha_s + \alpha_L)\ (\delta_1 - \delta_L) + V = 0 \tag{4}$$

In a similar way we can derive a formula for the heat balance of another plate with the same dimension, which is electrically heated and therefore free of dew. For two plates heated by the amounts H and 2 H (cal cm^{-2} min^{-1}) we get

$$S - (\alpha_L + \alpha_s)\ (\delta_2 - \delta_L) + H = 0 \tag{5}$$

$$S - (\alpha_L + \alpha_s)\ (\delta_3 - \delta_L) + 2H = 0 \tag{6}$$

The difference between (6) and (5)

$$H - (\alpha_L + \alpha_s)\ (\delta_3 - \delta_2) = 0 \tag{7}$$

and also the difference between (4) and (5)

$$V - H - (\alpha_L + \alpha_s)\ (\delta_1 - \delta_2) = 0 \tag{8}$$

are not influenced by the net radiation S_L and the air temperature.

If we measure with thermocouples, the temperature differences between three freely exposed plates, (1) unheated but possibly with dew formation, (2) and (3) electrically heate byd amounts H and 2H resp. but without dew, then we get between the plates (1) and (2) the thermoelectric voltage

$$U_1 = \tau (\delta_1 - \delta_2) = \frac{\tau}{\alpha_L + \alpha_s} (V - H) \tag{9}$$

and between the plates (2) and (3)

$$U_2 = \tau (\delta_3 - \delta_2) = \frac{\tau}{\alpha_L + \alpha_s} H, \tag{10}$$

where τ is the thermoelectric voltage of the thermocouples by a temperature difference of 1 deg. (mV/°C). The voltages U_1 and U_2 we can add electrically

$$U = U_1 + U_2 = \frac{\tau}{\alpha_L + \alpha_s} V \tag{11}$$

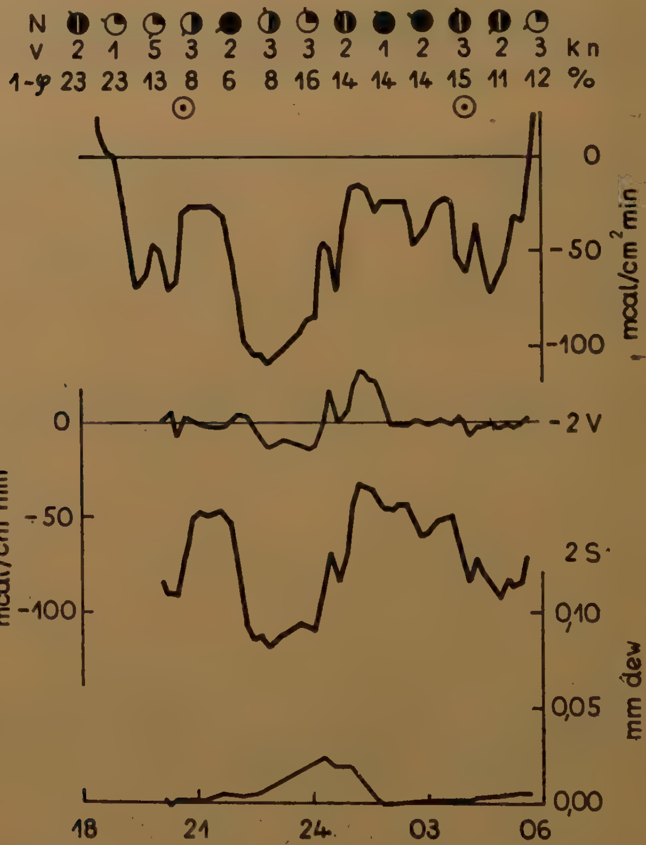
and record U and U_2. The recorded voltages U and U_2 depend somwehat on the temperature level (τ, α_s) but above all on the ventilation (α_L). By dividing

$$\frac{U}{U_2} = \frac{V}{H} \tag{12}$$

we can eliminate these influences and we get

$$V = H \frac{U}{U_2} \tag{13}$$

where H, U and U_2 are known values.



Dewfall (+ 2V) and net radiation (2S) of an artificial surface (plate) in a night with varying cloudiness. The upper curve gives the values of net radiation for the surrounding soil.

In a similar way it is also possible to measure the net radiation S by using one gilded and two blackened plates.

A thermoelectrical drosometer on this principle was developed at the Meteorological Institute of the University of Munich. Obviously the construction of the real instrument must give regard to influences not considered in the previous discussion on the principle e.g. influence of wind direction, heat flow between the plates etc. Therefore the theoretical derivation and the calculation of dew accretion from the record becomes considerably complicated for the real instrument (2).

The results (see fig.) show a good correlation between the dewfall (2 V, because the plate has two surfaces) and the net radiation, whether that of the plate (2 S) or that of the surrounding soil (upper curve, measured by a net radiation meter (4)). In a night with varying cloudiness the net radiation is the most changeable factor influencing the dewfall.

Generally the rate of dewfall W on a surface (instrument, plant, soil etc.) is given by

$$W = -\omega_s (S + B) - \omega_V \alpha_L (1 - \varphi) \qquad (14)$$

where ω_s and ω_V are coefficients increasing (3 ... 4 % p.deg.) with the temperature. S is the above-mentioned net radiation, B the heatflux from below (e. g. soil), α_L the heat transfer coefficient and $1 - \varphi$ the rel. saturation deficit (2). The last term of (14) represents an evaporation. It increases with increasing wind velocity(α_L) and decreasing relative humidity. In a saturated atmosphere it disappears. Then the first term gives us a possibility of calculating the maximum value of dewfall. Neglecting B, which can only decrease rate of dewfall by heat flux from below, we get with the high value of net radiation $S = -0{,}12$ cal cm^{-2} min^{-1} an accretion of dew of 0,07 mm h^{-1} or 0,7 mm during a night of ten hours (energetic limit of dew rate). Measurements of dewfall (1) show maximum values of this order of magnitude. In a normal night, however, the last term in (14) does not disappear and also the energy loss by radiation is smaller than the value used above. In the case of a normal night with strong dewfall we can therefore expect only 0,3 ... 0,4 mm. With increasing net radiation, increasing wind and decreasing relative humidity the rate of dewfall decreases until finally it becomes negative, that is evaporation, in which case (14) is again valid but only for a wet surface (3).

LITERATURE

(1) W. Gelbke, Untersuchungen zur Methodik der Taumessungen an Hand dreijähriger Taumeßreihen in Greifswald. *Abh. Met. Hydrol. Dienst DDR*, Nr. 38 (1955).

(2) G. Hofmann, Die Thermodynamik der Taubildung. *Ber. Deutsch. Wetterd.* Nr. 18 (1955).

(3) G. Hofmann, Verdunstung und Tau als Glieder des Wärmehaushalts. *Planta*, 4 303-322 (1956).

(4) Bericht über die Vergleichsversuche an Strahlungsmeßgeräten beim Meteorologischen Observatorium Hamburg zu Händen der Radiation Commission der I. A. M., I. U. G. G. 1. report 1955, 2. report 1956.

LES SOURCES SECONDAIRES D'HUMIDITÉ ET L'APPROVISIONNEMENT EN EAU DES SOLS DE LA FRANCE MEDITERRANEENNE

J. DAMAGNEZ
Institut National de la Recherche Agronomique
Station de Bioclimatologie agricole de Montpellier (France)

RÉSUMÉ

L'auteur souligne qu'en raison d'une pluviométrie estivale rare et irrégulière, les recherches concernant les sources secondaires d'humidité du sol présentent sous le climat méditérranéen une grande importance agronomique.

Une analyse des phénomènes d'échange d'eau entre l'atmosphère et le so conduit à des recherches menées conjointement et qui concernent :

1) — Les conditions climatiques (hygrométrie, turbulence, température...) au voisinage de la surface du sol.

2) — Les relations physico-chimiques entre le sol et la vapeur d'eau. On envisage les équilibres d'hygroscopicité et les conditions de diffusion de la vapeur d'eau dans un milieu poreux.

Une technique appropriée d'enregistrement des variations de poids d'un volume déterminé de terre et l'utilisation d'un écran limitant le rayonnement nocturne permettent de dissocier, en première approximation, les phénomènes de condensation des phénomènes de fixation directe de la vapeur d'eau. Une méthode de classement des données expérimentales permet alors d'interpréter l'action d'un seul des facteurs physiques, les autres restant sensiblement constants.

On montre l'action prépondérante de la tension de la vapeur d'eau dans l'atmosphère sur ces apports. L'auteur précise comment l'intensité de ces processus croît quand l'humidité du sol diminue. Le point de flétrissement permanent est un seuil à partir duquel la fixation directe augmente rapidement en raison de la diminution très rapide de la tension de vapeur d'eau en équilibre avec le sol.

Les phénomènes observés peuvent entraîner une variation d'humidité de 2 % dans la couche superficielle. On conçoit alors l'importance de ces phénomènes sur la vie microbienne et la nitrification.

I — INTRODUCTION

En raison de la rareté des pluies pendant l'été méditerranéen, les recherches concernant les apports vers le sol d'eau provenant des phénomènes de condensation et de l'adsorption directe de la vapeur d'eau atmosphérique présentent dans le Midi de la France une grande importance agronomique.

Ces problèmes ont d'ailleurs retenu depuis longtemps l'attention des écologistes et des hydrologistes. Déjà en 1924, L. CHAPTAL à MONTPELLIER (1) avait commencé l'étude de ces apports occultes. L'Organisation Météorologique Internationale l'avait chargé au cours de sa réunion de DANTZIG en 1937 d'effectuer une enquête sur l'intérêt des sources secondaires d'humidité et sur l'état d'avancement des recherches dans ce domaine. Pour les pays de l'Europe du Nord les réponses firent ressortir qu'en raison d'une pluviométrie généralement assez bien répartie l'intérêt des sources secondaires d'humidité est faible. Par contre, dans les régions à climat de type méditerranéen, la pluviométrie devient tellement irrégulière que la notion de moyenne s'efface devant celle de fréquence (2) et la rareté des précipitations pendant les trois mois d'été domine complètement les conditions de la vie végétale. Or ici les réponses soulignent toutes que l'aspect de la végétation spontanée dans ces régions ne traduit pas toujours ces conditions sévères.

Tenant compte de ces faits d'observation tous les correspondants sont alors conduits à faire l'hypothèse que les sources secondaires d'humidité provenant de la rosée et de la fixation de la vapeur d'eau atmosphérique peuvent contribuer à satisfaire les besoins en eau de la végétation.

Mais il semble que le plus souvent faute d'expérimentation on a dû se contenter d'invoquer de tels phénomènes sans pouvoir en estimer exactement l'importance. Et, malgré l'intérêt unanimement reconnu de cette question, le phénomène de fixation de la vapeur d'eau atmosphérique semble avoir été peu étudié. Par ailleurs la diversité des dispositifs de mesure utilisés en drosométrie rendent très difficile l'interprétation des mesures relatives à la rosée. Ainsi l'absence ou la disparité des résultats nous ont incité à rechercher une méthode d'étude intrinsèque des phénomènes de fixation et de condensation de la vapeur d'eau atmosphérique.

II — Relations physico-Chimiques entre la vapeur d'eau et le sol

Les phénomènes de rosée et de condensation interne, essentiellement liés au point de rosée de l'air et au minimum thermique atteint par le sol au cours de la nuit, constituent l'une des sources secondaires d'humidité des sols. Mais les apports occultes comprennent également une fixation directe de la vapeur d'eau atmosphérique dans le sol, liée à un processus général d'adsorption. Il est donc nécessaire pour étudier ce dernier phénomène de préciser les relations physico-chimiques entre la vapeur d'eau et le sol et plus particulièrement leur aspect dynamique.

On sait que l'établissement d'un équilibre d'adsoprtion est théoriquement instantané. Mais dans un milieu tel que le sol, le phénomène est évidemment limité par la diffusion de la vapeur d'eau à l'intérieur même de la masse, processus dont la vitesse est relativement lente.

Pour aborder l'étude de la *dynamique de l'adsorption* dans l'épaisseur du sol, il faut donc envisager tout d'abord les équilibres d'hygroscopicité aux différentes températures et ensuite les conditions de diffusion de la vapeur d'eau dans le milieu poreux que constitue le sol.

1°) — *Equilibre d'hygroscopicité*

Il n'est pas dans notre intention d'analyser ici la nature intime du processus de fixation, fort complexe dans le cas du sol en raison de sa forte proportion de colloïdes argileux. Adsorption physique, adsorption chimique et imbibition sont autant de phénomènes différents qui se superposent mais dont la résultante est cependant connue. Sur le plan énergétique, le processus global est réglé par une fonction que l'on a coutume d'appeler potentiel capillaire ψ. Il est défini, rappelons le, comme étant la différence d'énergie libre entre un gramme d'eau liée au sol et un gramme d'eau libre. Ce potentiel est lié à la tension de vapeur f_s en équilibre avec l'eau du sol à la température T par la relation de Gibbs, où $F_{(t)}$ est la tension saturante de la vapeur d'eau à la même température :

$$\psi = \frac{RT}{M} \log \frac{F_{(t)}}{f_s}$$

Equilibre d'hygroscopicité et condensation capillaire. — Le domaine de validité de cette formule est étendu. Dans le cas des phénomènes capillaires, on peut cependant particulariser le problème et expliciter la valeur de ψ en fonction de données directement accessibles. Lord Kelvin a établi pour la température T la loi exprimant l'état

hygrométrique de l'atmosphère en équilibre avec l'eau d'un ménisque dont le rayon est r :

$$\text{Log} \frac{f_s}{F_{(t)}} = - \frac{2\gamma}{r} \times \frac{V'}{RT}$$

Dans cette formule V' est le volume molaire de l'eau liquide et γ sa tension superficielle. Cette relation montre que si un capillaire du sol est suffisamment fin, un phénomène de condensation capillaire peut se produire pour des tensions de vapeur notablement inférieures à la tension saturante. Ainsi pour un capillaire ayant 0,02 μ de diamètre, l'état hygrométrique de l'atmosphère en équilibre est 0,897 à la température de 20° C.

Or, autour des aggrégats du sol tout un réseau semi-capillaire constitue l'espace lacunaire où circulent l'eau et l'air. Un deuxième réseau de capillaires beaucoup plus fins et par conséquent *tensio-actifs* se situe à l'intérieur des aggrégats eux-mêmes où les phénomènes sont régis par la formule précédente. On peut concevoir dans ces conditions un processus de fixation par *condensation capillaire* se produisant de la surface du sol vers les couches inférieures, pour des tensions de vapeur nettement inférieures à la tension saturante.

2°) — *Diffusion de la vapeur d'eau dans le sol*

L'eau peut être ainsi accumulée à certains niveaux par ces divers processus : fixation directe et condensation capillaire si la température du sol est supérieure au point de rosée de l'air; rosée proprement dite en surface à partir du moment où la vapeur devient saturante. De ces couches rendues ainsi plus humides, la vapeur d'eau est alors susceptible de diffuser dans le milieu poreux qu'est le sol. On soulignera ici l'aspect du phénomène en régime isotherme et permanent.

Dans le cas d'un cylindre dont les parois n'auraient aucune affinité vis-à-vis de la vapeur d'eau, le phénomène de diffusion serait représenté par l'équation de diffusion sous sa forme classique :

$$\frac{dq}{dt} = - DS \frac{dn}{dz}$$

où dq/dt est le débit, dn/dz le gradient de concentration, S la section du cylindre et D le coefficient de diffusivité moléculaire.

Dans le cas du sol, on introduit tout d'abord deux facteurs de correction dûs respectivement à la *tortuosité* et à la *porosité* ([3]). Mais en raison de l'affinité des molécules d'eau pour les constituants du sol, il semble que cette manière de voir ne soit pas suffisamment représentative des faits : certains auteurs ([4]) ont en effet constaté expérimentalement un coefficient de diffusion de la vapeur d'eau dans le sol nettement plus élevé. Mais quoiqu'il en soit, la répartition de la tension de la vapeur d'eau dans un sol est alors telle que le déficit de saturation ($F_{(t)} - f_s$) de l'atmosphère du sol décroît en fonction de la profondeur selon une loi exponentielle ([5]).

III — Etude expérimentale des phénomènes de condensation et de fixation de la vapeur d'eau atmosphérique

Dispositif expérimental et technique utilisée. — La méthode suivie comporte l'étude au cours de la nuit des variations de poids d'un volume déterminé de terre fine au moyen de balances enregistrantes. La terre utilisée, un limon calcaire passé au tamis de 2 mm, est placée sur une épaisseur de 5 cm dans un récipient métallique

de 24 × 24 cm et réhumectée « per ascensum » à un taux d'humidité donné qui, au cours de cette note, est exprimé en p. cent de terre sèche.

Deux de ces systèmes expérimentaux sont mis en service simultanément. Dans le premier cas, la surface de la terre est exposée « à découvert ». Le rayonnement nocturne n'étant ainsi pas limité, la température à la surface du sol atteint la température du point de rosée de l'air pour la plupart des nuits d'observations. Dans ces conditions, on enregistre une augmentation de poids correspondant évidemment à un *double phénomène de condensation et d'adsorption.*

Dans le second cas, on cherche à éliminer le phénomène de condensation afin d'enregistrer uniquement l'accroissement de poids dû à la fixation de la vapeur d'eau. Dans ce but, on place au-dessus du dispositif expérimental un écran de dimensions appropriées qui réduit d'environ 70 p.-cent le rayonnement effectif du sol vers l'atmosphère durant la phase nocturne. On maintient ainsi pour de nombreuses nuits d'observations la surface du sol à une température supérieure au point de rosée de l'air et seule subsiste la *fixation de la vapeur d'eau.* Par nuit de fort rayonnement, l'écart de température entre les deux systèmes considérés varie de 3 à 4°C et peut même atteindre 5°C par temps calme.

On dissocie de cette manière en première approximation, le phénomène globalement enregistré en ses deux composantes : condensation et fixation de la vapeur d'eau atmosphérique.

Données climatiques utilisées. — L'évolution thermique de la surface d'échange considérée est caractérisée par les températures lues sur un thermomètre placé horizontalement à la surface du sol. La *température minimum* a été prise comme donnée de référence.

Les conditions d'humidité de l'air au voisinage de la surface d'échange ont été caractérisées par la *tension de vapeur* f_a et la température du point de rosée correspondante obtenues à partir des données classiques sous abri à deux mètres. On a supposé, en première approximation, que le gradient de tension de vapeur durant la phase nocturne entre deux mètres et la surface du sol est suffisamment faible pour être négligé.

Enfin le pouvoir évaporant de l'air E a été déterminé par les lectures faites entre 17 h. et 6 h. T. U. le lendemain à l'Evaporomètre de Piche sous abri. Toutes choses étant égales par ailleurs, cette donnée est fonction de la turbulence et influe par conséquent sur la valeur du gradient thermique au voisinage de la surface; elle a donc une action indirecte sur les conditions de diffusion de la vapeur d'eau de l'air vers le sol.

Méthode de dépouillement des données recueillies. — La méthode de dépouillement s'inspire de celle utilisée en Ecologie par H. Geslin (6) puis par M. Godard (7) : Un classement judicieux des données journalières recueillies en un certain nombre de cas définis permet d'effectuer l'analyse d'un seul des facteurs d'action, les autres facteurs étant constants. On peut ainsi mettre en évidence l'action propre d'un facteur puis d'un complexe climatique.

La température minimum atteinte par la surface de la terre a permis de préciser si cette température était inférieure ou supérieure au point de rosée de l'air. On peut alors pour chaque nuit d'observation distinguer la nature exacte du phénomène.

Enfin pour tenir compte de l'influence de la turbulence de l'air sur les deux phénomènes étudiés, seules ont été classées les nuits d'observation au cours desquelles le pouvoir évaporant de l'air est resté inférieur à 2 mm.

Dans le groupe de nuits ainsi retenues, on a recherché celles où la température minimum de la surface du sol resta comprise entre des limites aussi rapprochées que possible. Seule varie alors, d'une nuit à l'autre, la tension de vapeur f_a. On a pu ainsi

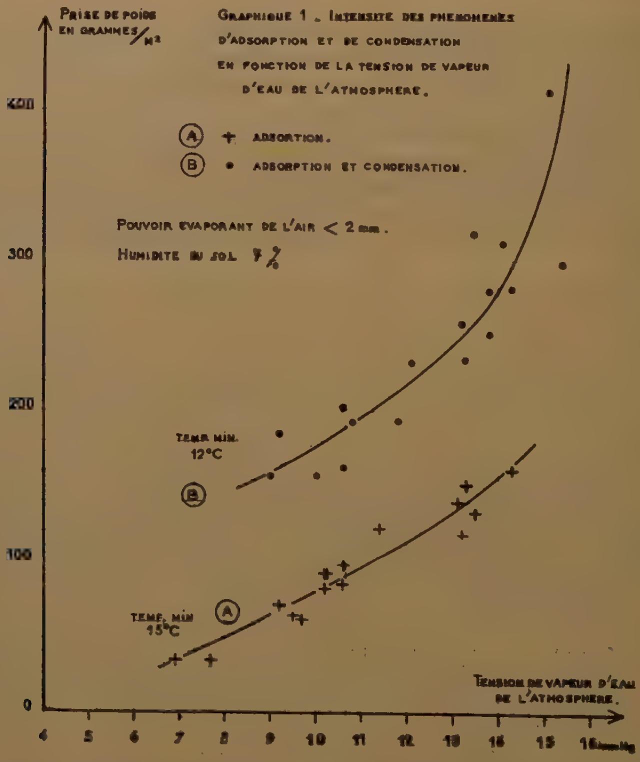
mettre en évidence la relation entre la tension de vapeur f_a et le gain global d'humidité du sol d'épreuve, à température et à pouvoir évaporant de l'air constants.

IV — Résultats expérimentaux

A — *Influence de la tension de vapeur d'eau atmosphérique*

Les résultats présentés sont relatifs à une couche de terre de 5 centimètres d'épaisseur, sensiblement maintenue à 7 p. cent d'humidité globale, soit dans le cas présent légèrement en dessous du point de flétrissement.

1) *Fixation de la vapeur d'eau.* — Les courbes obtenues à partir de la méthode de dépouillement expliquée ci-dessus mettent en évidence l'action prépondérante de la tension de vapeur d'eau f_a de l'atmosphère durant la phase nocturne sur le phénomène de fixation. Ainsi pour un pouvoir évaporant de l'air faible (E $<$ 2 mm) et pour différentes nuits d'observation où la température minimum de la surface du sol atteignit une même valeur voisine de 15° C (courbe A, graph. 1) l'intensité du phénomène de fixation est multipliée par 2, passant de 80 gr à 180 gr par mètre carré, si la tension de vapeur f_a passe de 10,5 à 15 mm de Hg.



Graphique 1 . Intensite des phenomenes d'adsorption et de condensation en fonction de la tension de vapeur d'eau de l'atmosphere.

Ce phénomène de fixation est très fréquent au cours de la saison chaude. A Montpellier où la tension moyenne de la vapeur d'eau dans l'atmosphère est

d'environ 12 mm de Hg de juin à août, on peut compter ainsi sur un apport presque quotidien de l'ordre de 110 grammes par mètre carré sous l'action du seul processus de fixation. Cette quantité représente très certainement, comme il sera précisé plus loin, un minimum car pour un sol en place les conditions de mulch au cours de la saison chaude sont très prononcées.

2) *Fixation et condensation.* — Pour le même échantillon de terre mais placé cette fois à découvert, la quantité d'eau incorporée au sol provient à la fois des phénomènes de condensation et de fixation de la vapeur d'eau atmosphérique. Elle est beaucoup plus importante comme le montre la courbe B (graph. 1). Les nuits retenues pour construire cette courbe sont les mêmes en général que celles utilisées pour étudier l'adsorption du système placé sous écran (courbe A), mais à cause du rayonnement nocturne, la température minimum est ici plus basse : Elle reste dans tous les cas voisine de 12° C. Dans ces conditions la quantité d'eau incorporée au sol au cours d'une nuit peut atteindre 410 gr/m².

3) *Fréquence du phénomène de condensation et état hygrométrique de l'air.* — On a admis en première approximation que le gradient de tension de la vapeur d'eau dans les couches d'air au voisinage du sol est faible durant la nuit en raison de sa grande diffusivité. Cependant, par suite du refroidissement très marqué du sol au cours de la nuit, l'humidité relative présente sa plus grande valeur au voisinage de la surface. Par temps clair, il en résulte que la rosée se dépose alors que l'air au niveau de l'abri est encore très loin du point de saturation. M. GODARD [8] indique que sous le climat de MONTPELLIER plus de 20 p. cent des rosées, dont certaines abondantes, se produisent alors que le maximum de l'état hygrométrique sous l'abri reste compris entre 60 et 90 degrés hygrométriques (tableau I).

TABLEAU I

Etat hygrométrique et fréquence des rosées 1946-1948 — MONTPELLIER — Station de Bel-Air

Maximum de l'Etat hygrométrique nocturne compris entre	100 et 90	89 et 80	79 et 70	69 et 60
Nombre de rosées par an	83	16	5	1
Fréquence annuelle en p. cent du nombre total	79	15	5	1

La rosée étant observée sur les brins d'herbe, on conçoit que sa fréquence puisse ainsi être élevée en raison de la température relativement basse atteinte par le gazon sous l'effet du rayonnement nocturne. Cependant, *sur sol nu*, nos expériences ont montré que pour des états hygrométriques maxima sous abri assez éloignés du point de saturation, la condensation pouvait également être notable. Le tableau II présente les quantités d'eau condensées * au cours de nos essais pour différents états hygrométriques.

* La quantité d'eau condensée est obtenue par la différence entre l'intensité du phénomène globalement constaté (condensation + fixation) et l'intensité de la fixation.

TABLEAU II

Etat hygrométrique maximum et intensité des phénomènes de condensation
(Montpellier 1956 — Humidité du sol : 7 p. cent)

Etat hygrométrique maximum sous abri au cours de la nuit	90	80	70
Quantité d'eau condensée en gr/m^2	135	100	65

B — *Influence de l'humidité du sol*

On a pu également préciser l'action propre des facteurs liés au sol et notamment *son humidité.*

1) *Aspect théorique du phénomène*

La formule de Gibbs montre combien l'état d'humidité commande l'énergie de fixation de l'eau par le sol; celle-ci augmente rapidement pour des humidités du sol inférieures au point de flétrissement et la tension de vapeur d'eau en équilibre avec le sol correspond alors à une tension de vapeur f_s caractéristique, inférieure à la tension saturante $F_{(t)}$. L'étude théorique des phénomènes sera tout d'abord précisée en régime isotherme puis en régime variable. Les faits tendant à une vérification expérimentale seront ensuite exposés.

a) *Régime isotherme.* — Dans un sol en régime isotherme si la tension de vapeur f_s est supérieure à la tension de vapeur d'eau f_a dans l'atmosphère surmontant le sol, on observe un phénomène d'évaporation. Si au contraire $f_s < f_a$, des apports d'eau se produisent vers le sol par adsorption ou condensation capillaire. Dans ces conditions, on peut prévoir que plus la tension de vapeur f_s^o en équilibre avec la surface du sol sera faible par rapport à la tension de vapeur f_a de l'atmosphère surmontant le sol, plus le phénomène de fixation sera intense.

Sur la fig. I ont été schématisé les phénomènes correspondant à des états de dessiccation du sol plus ou moins avancés, l'atmosphère des couches profondes

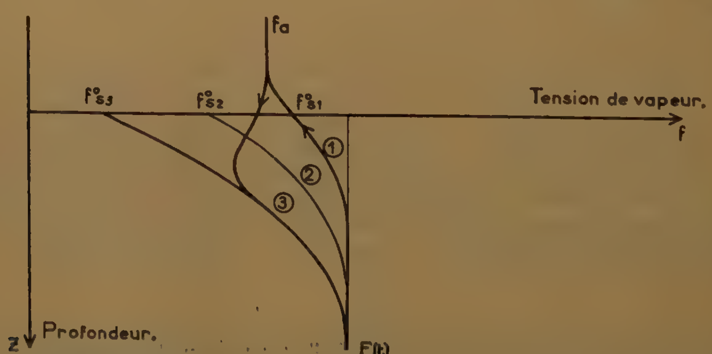


Fig. I — Humidité du sol et fixation de la vapeur d'eau — *Régime isotherme.*

restant cependant saturée (tension $F_{(t)}$). La courbe (1) correspond encore à un phénomène d'évaporation. Les courbes (2) et (3) correspondent au contraire à un phénomène de fixation d'autant *plus intense et plus pénétrant* que $(f_a - f_s^o)$ est plus grand, donc que le sol est plus sec.

b) Régime variable. — Dans les conditions naturelles, l'amplitude de l'oscillation thermique journalière affectant les couches superficielles du sol peut alors commander ou modifier, si le dessèchement de ces couches est suffisant, le sens de la diffusion. Les phénomènes sont schématisés sur la fig. II où f_a est la tension de vapeur d'eau atmosphérique, tension supposée sensiblement constante s'il ne survient aucun changement de masse d'air au cours d'une journée. La courbe (1) représente sensiblement le profil des tensions saturantes de la vapeur d'eau à l'instant où se produit le maximum thermique dans les couches du sol immédiatement voisines de la surface. La courbe (2) indique la tension réelle de vapeur d'eau en équilibre avec le sol aux différents niveaux au même moment. Si la tension de vapeur f_s^o en équilibre avec le sol en surface est supérieure à la tension de vapeur d'eau dans l'atmosphère f_a ceci entraîne, ainsi qu'il a été vu, un phénomène d'évaporation. Mais dès que le maximum thermique s'est produit, la tension de vapeur f_s^o s'abaisse car elle est liée à $F_{(t)}$ en raison de la formule de GIBBS. Elle peut très rapidement devenir inférieure à la tension de vapeur d'eau dans l'atmosphère f_a et les conditions sont alors favorables à un processus de fixation. On peut prévoir ainsi que le phénomène de fixation doit débuter dans le cas d'un mulch très prononcé peu après que le maximum thermique se soit produit à la surface du sol. La chute de température se poursuivant, un phénomène de rosée se produira alors dès que le point de rosée à la surface du sol sera atteint, c'est-à-dire lorsque $F_{(t)} \leqslant f_a$.

Le matin au moment du minimum thermique, on observera donc un profil de tension de vapeur en équilibre avec l'humidité du sol tel que (4). Si aucun phénomène d'apport ne s'était produit on aurait alors observé le profil (3). Le gain net d'humidité qui se traduit sur ce schèma par l'augmentation de la tension de vapeur en équilibre avec le sol, correspond donc à la zone hachurée.

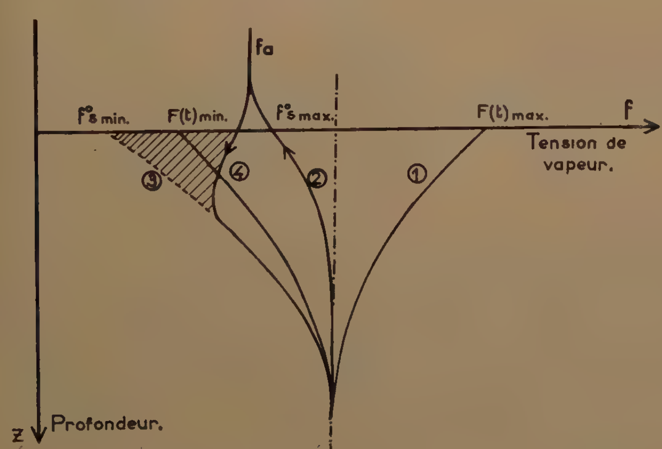


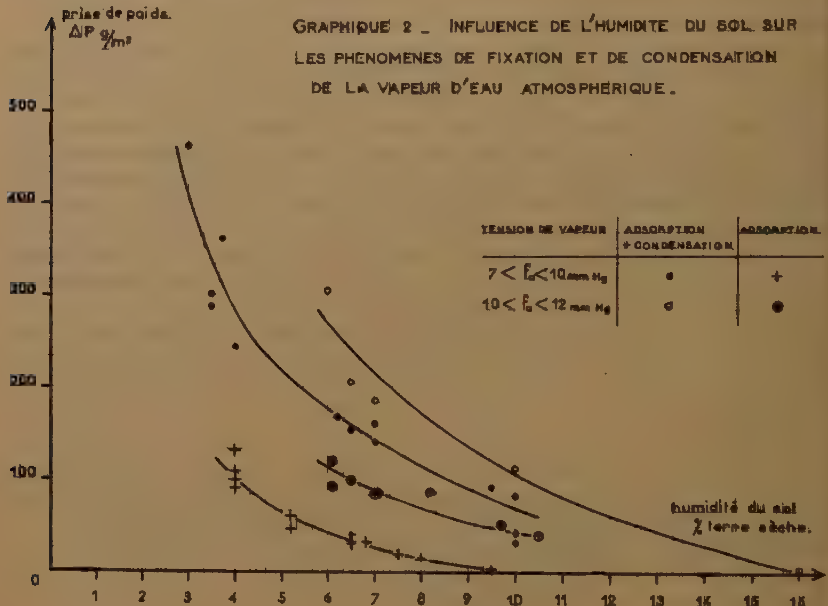
Fig. II — Humidité du sol et fixation de la vapeur d'eau — *Régime variable.*

2) *Vérifications expérimentales*

La confrontation de ces vues théoriques avec les faits expérimentaux aboutit aux conclusions suivantes :

a) La prise de poids est bien effectivement un phénomène précoce. — L'enregistrement des variations de poids d'un volume de terre montre en effet que la prise d'humidité par le sol commence bien avant le coucher du soleil. Toutes conditions étant égales par ailleurs le gain d'humidité commence d'autant plus tôt que l'humidité du sol est faible. Ainsi pour un mulch très prononcé le phénomène peut débuter vers 15 heures T. U. soit quatre heures avant le coucher du soleil alors que l'humidité relative de l'air sous abri n'est que de 36 p. cent. Ce résultat inattendu à première vue est donc bien en accord avec ce que laissait prévoir l'analyse théorique précédente.

b) Le phénomène de fixation est d'autant plus intense que l'humidité du sol est plus basse. — Une étude des phénomènes de fixation et de condensation pour des humidités variables du sol d'épreuve et le classement des données recueillies selon la méthode de dépouillement précédemment adoptée ont permis de tracer les courbes représentés sur le Graph. 2.



Dès que le seuil de 9 à 10 p. cent d'humidité globale est atteint, ce qui correspond pour le limon considéré sensiblement au point de flétrissement permanent, l'intensité des phénomènes de fixation directe et même de condensation croît très rapidement. Ainsi pour une humidité du sol de 3 à 4 p. cent, correspondant à un état de mulch fréquent à MONTPELLIER en été, le graphique montre que ces gains augmentent fortement. Ils seraient encore plus accentués pour la valeur moyenne de la tension de vapeur d'eau f_a atmosphérique en juillet-août qui atteint 12 mm environ.

C — *Localisation dans le sol des phénomènes de condensation et de fixation*

L'ensemble des faits observés conduit enfin à étudier la répartition dans le sol des phénomènes de condensation et de fixation en fonction des profils thermique et hydrique.

1) *Dépouillement climatique*

Les différents facteurs du climat du sol permettent d'analyser la fréquence des phénomènes dans les couches affectées par l'oscillation thermique journalière. En l'absence de données précises sur la tension de vapeur d'eau f_s en équilibre avec le sol à différentes profondeurs, on s'est limité à l'étude de la *condensation proprement dite*.

En considérant la tension de vapeur d'eau f_a de l'atmosphère au cours de la nuit et la température du sol en place à différents niveaux au voisinage de la surface, on a déterminé le nombre de jours où la température du point de rosée de l'air est atteinte aux différentes profondeurs, (Tableau III).

TABLEAU III

Température du sol et fréquence du phénomène de condensation — (*Montpellier — 1952*)

	Nombre de jours p. cent où le point de rosée a été atteint à différents niveaux			Fréquence du phénomène à différents niveaux en p. cent de la fréquence en surface		
	Surface	— 0,7 cm	— 5 cm	Surface	— 0,7 cm	— 5 cm
Printemps	50	38	3	100	76	6
Eté	27	12	0	100	44	0

Le tableau III montre que les possibilités de condensation dans le sol diminuent très rapidement, même au voisinage immédiat de sa surface. Dans la couche superficielle, c'est seulement de 0 à 5 cm de profondeur que des condensations peuvent se produire au cours de la saison chaude sous le climat de MONTPELLIER. Mentionnons qu'en raison des variations saisonnières de la température dans le sol de telles possibilités réapparaissent à un mètre environ.

2) *Etude expérimentale directe*

Afin de préciser les niveaux où se produisent les différents apports d'humidité, une technique expérimentale appropriée a été élaborée. Un lot de cylindres est rempli de terre fine qui a été amenée par réhumectation à une humidité connue aussi homogène que possible. Le lot de cylindres ainsi préparé est placé au début de l'après-midi dans une parcelle de sol nu : seules affleurent au niveau général du sol, les surfaces d'échange expérimentales. En raison du diamètre suffisamment faible des cylindres, les conditions thermiques aux différents niveaux deviennent rapidement comparables à celles correspondant aux couches superficielles d'un sol en place comme cela a été vérifié.

Au coucher du soleil, un dosage d'humidité par tranche de 1 centimètre, sur un certain nombre de cylindres, fait connaître le profil hydrique de départ. Un dosage analogue effectué le lendemain matin au lever du soleil, permet de tracer le profil d'arrivée. On a pu ainsi, par la comparaison des deux profils, mettre en évidence une augmentation de l'humidité du sol et calculer le gain net à chaque niveau.

TABLEAU IV

Localisation dans la masse du sol des phénomènes de condensation et de fixation
(Nuit du 16 au 17 juillet 1956)
Humidité de la couche 0-5 cm : 6,3 p. cent

Profondeurs :		0-1 cm	1-2 cm	2-5 cm	Total 0-5 cm
Variation du taux d'humidité au cours de la nuit		+1,9 %	+0,4 %	Ecarts non significatifs	
Prise de poids g/m²	*mesurée*	+209	+ 44		**253**
	calculée *				**245**

* à partir des graphiques 1 et 2 et des données climatiques de la nuit considérée.

Le Tableau IV résume les résultats relatifs à l'une des nuits d'observation (16 au 17 juillet 1956). La tension de vapeur d'eau atmosphérique au cours de cette nuit resta voisine de 10,8 mm de Hg, correspondant à un point de rosée de 12°5, alors que la température minimum à la surface d'échange atteignit 12,2°C : on nota effectivement une faible rosée le matin. Cependant, au cours de cette même nuit, la température minimum à 0,7 cm dans le sol était de 12,9°C, c'est-à-dire supérieure à la température du point de rosée de l'air. Ce fait élimine donc la possibilité d'un phénomène de condensation dès 0,3 cm de profondeur environ. Au-dessous de ce niveau, le phénomène de condensation étant exclu, le gain d'humidité constaté correspond donc au seul *processus de fixation* dont l'existence se trouve ainsi mise en évidence.

Ces résultats ont été comparés avec les quantités d'eau apportées au sol par condensation et fixation, calculées à partir des courbes (graph. 1 et 2) obtenues précédemment. La concordance des résultats obtenus dans les deux cas est satisfaisante comme le montre le Tableau IV, col. 4. Il semble donc qu'on puisse prévoir la fréquence et l'intensité des sources secondaires d'humidité à partir de données physico-chimiques concernant le sol et de facteurs climatiques directement accessibles.

V — Conclusion

Ces premières recherches montrent qu'il est possible par une méthode intrinsèque de situer l'ordre de grandeur des apports au sol de l'eau provenant des sources secondaires d'humidité.

Les dispositifs expérimentaux réalisés à cet effet ont permis de mettre en évidence que les phénomènes étudiés sont, dans le cas d'une terre limoneuse, essentiellement localisés à la couche tout à fait superficielle du sol et que la quantité d'eau apportée chaque nuit est suffisante pour en augmenter de 2 p. cent le taux d'humidité. Ces apports sont encore plus marqués lorsque celui-ci s'abaisse fortement au-dessous du point de flétrissement. De telles conditions du sol correspondent à un mulch prononcé : elles sont fréquemment réalisées à Montpellier puisqu'en juillet par exemple, seuls deux à trois jours de pluie supérieure à 1 mm y sont observés en moyenne.

On peut penser que ces apports d'humidité puissent favoriser la vie microbienne car, ainsi que l'ont montré Ch. Killian et D. Feher ([8]) sous un climat aride, la flore

microbienne et en particulier les bactéries de la nitrification manifestent déjà une forte activité pour des taux d'humidité du sol relativement bas. G. LEFEVRE et G. DROUINEAU (10) ont par ailleurs mis en évidence l'accumulation estivale, en l'absence de pluie, de la forme minéralisée de l'azote dans la couche superficielle du sol sous un climat de type méditerranéen, sans qu'une remontée capillaire puisse être invoquée. On peut alors supposer que l'humidité atmosphérique, condensée et fixée par la couche superficielle du sol au cours de la nuit, favorise l'action microbienne de minéralisation. Ce serait là, outre leur contribution au bilan hydrique, un aspect agronomique très important des sources secondaires d'humidité.

Dans un autre ordre d'idées, ces phénomènes de fixation et de condensation pourraient justifier certaines constatations faites par A. RONDEAU (11) en Corse sous climat méditerranéen sur la vitesse d'altération par hydrolyse acide de certaines roches basiques dures telles que les Diorites.

BIBLIOGRAPHIE

(1) CHAPTAL (L.) — *Annales Agronomiques* — 1928/134-153. 1930/69-77.
(2) VERNET (A.) et MARGER (J.) — *Annales Agronomiques* — 1946/329-340.
(3) PENMAN (H. L.) — *J. of Agricultural Science* — 1940/30/437-462.
(4) TAYLOR (S. A.) et CAVAZZA (L.) — *Soil Science Society of America Proceedings* — 1954/18/351-358.
(5) HALLAIRE (M.) — *C. R. VI° Congrès international de la Science du sol*, Paris 1956/I/48.
(6) GESLIN (H.) — Thèse Faculté des Sciences — Paris 1944.
(7) GODARD (M.) — *C. R. VIII° Congrès international de Botanique* — Paris 1954/XI et XII/256-258.
(8) GODARD (M.) — *Annales Agronomiques* — 1949/Série A/578-604.
(9) KILLIAN (Ch.) et FEHER (D.) — *Annales de l'Institut Pasteur* — 1935/55/573-623.
(10) LEFEVRE (G.) et DROUINEAU (G.) — *Annales Agronomiques* — 1951/Série A/1-12.
(11) RONDEAU (A.) — *Bulletin Association des Géographes français* — 1956/217-218 49-61.

LA CONTRIBUTION DE L'ITALIE A L'ÉTUDE DES CONDENSATIONS ATMOSPHÉRIQUES

PROF. M. VISENTINI ET PROF. M. VANNI

RÉSUMÉ

On donne des indications sur les recherches effectuées en Italie pour déterminer les condensations atmosphériques ou précipitations occultes sur les régions glaciales et sur celles à climat chaud et humide.

Le problème de la contribution, rapportée à la formation des condensations occultes, a attiré l'attention des hydrologues même en Italie dans le but de déterminer la mesure et expliquer la valeur du coefficient d'écoulement sur plusieurs bassins hydrographiques, surtout là où le sol est recouvert de neige ou de glaciers.

Nos hydrologues les plus connus, tels Fantoli, Alfieri, Volta, Gherardelli, Visentini, Merla, Baronio et en outre Monterin illustre glaciologue, se sont tous occupés plus ou moins de ce sujet dans une série d'importantes études sur les écoulements et sur l'ablation glaciaire..

M. Volta ([1]), dans son étude sur le régime des lacs lombards par rapport à la contribution glaciaire, a été le premier qui, en 1921 a attiré l'attention sur ces formes de condensations; vinrent ensuite les travaux de Fantoli ([2]) qui s'occupa particulièrement du lac de Côme et recueillit aussi quelques données sur la probabilité de la contribution des condensations occultes, limitées cependant à une période assez courte, le mois d'août; Monterin par la suite, considéra ces données très supérieures à la vérité.

Les études de M. Alfieri ([4]) ([5]) sont aussi fort intéressantes; il s'occupa surtout des cours d'eau piémontais : le Tanaro, la Dora Baltea et la Dora Riparia dont les bassins versants présentent un développement glacial différent. La comparaison démontre que la Dora Riparia et le Tanaro présentent un déficit de l'écoulement par rapport à l'efflux : par contre la Dora Baltea, dont le bassin présente de vastes surfaces glaciaires, présente un coefficient d'écoulement supérieur à 1. De ce fait il en dérive l'importance que les condensations occultes doivent avoir par rapport aux surfaces recouvertes de neige et de glaciers par rapport aux surfaces rocheuses ou recouvertes de terre végétale. Monterin devait démontrer aussi que sur les glaciers ce phénomène devenait très important. Gherardelli ([3]), Baronio ([6]) et Visentini ([7]) dans leurs études attirèrent l'attention et firent quelques remarques sur ces condensations.

En 1937, M. Merla dans ses recherches sur le glacier des Forni, devait apporter une importante contribution à l'étude des condensations, en nous donnant des données de mesures déduites de la comparaison entre les précipitations, les écoulements et l'ablation de la masse glaciaire le tout déduit des observations spécifiques et des relevés des variations du glacier pendant une période de dix ans.

Une étude plus soignée a été publiée enfin en 1939 par Monterin, illustre spécialiste en glaciologie. Son étude représente une analyse minutieuse et une nouvelle élaboration de nombreuses données sur les condensations occultes, receuillies avec des contrôles méthodiques dans les observations du Mont Rosa. M. Monterin put faire la comparaison entre le phénomène qui se produit au fond de la vallée, en moyenne montagne (Col d'Olen 2900 m) et en haute montagne (Capanna Margherita 4560 m).

Les résultats, obtenus par lui, ne concordent pas cependant avec ceux obtenus

par d'autres hydrologues italiens et même étrangers. Monterin obtient une contribution annuelle de 8,75 l/s km^2 pour la surface de glace et de 4,14 l/s km^2 pour la surface de tout le bassin. Ceci met surtout en évidence l'importance de la condensation sur les glaciers et les champs de neige, véritables condensateurs d'humidité. Selon ce que nous avons dit, les données de Monterin sont cependant inférieures à celles obtenues par d'autres savants.

En effet Forel pour le glacier du Rhône trouve 42 l/s km^2; Fantoli pour le lac de Côme (mois d'août) 25 l/s km^2 et enfin Merla juge que les condensations occultes sur le bassin versant du glacier des Forni peut être de 22 l/s km^2 tandis que sur le glacier seul il pourrait se réduire à 5 l/s km^2.

Comme on le voit les résultats selon les divers auteurs sont assez différents; le phénomène demande encore de longues études et une parfaite organisation; quelque recherche est actuellement en cours sur le glacier de Valtournanche (Val d'Aoste) par l'initiative du Comité Italien de Glaciologie; les mesures ont été confiées aux soins du géomètre De Gemini. Plusieurs données ont déjà été receuillies mais leur élaboration n'est pas encore terminée.

Dans un domaine différent de celui ci-dessus énoncé on doit rappeler : a) les études et les recherches du Prof. Henry Pantanelli [11] sur les valeurs de la condensation occulte sur la plaine des Pouilles par rapport surtout à la contribution que ce phénomène donne au développement de la végétation dans les périodes de sécheresse; b) les recherches faites par l'Ing. Francesco Sensidoni [12] sur les condensations atmosphériques en Marmarique et sur la Syrte (Afrique du nord) pour leur utilisation à des fins potables.

BIBLIOGRAPHIE

(1) Volta L. — « Il regime dei laghi Maggiore, di Lugano e di Como durante il quindicennio 1902-1916 in rapporto alla determinazione del contributo glaciale » — *Bollettino Comitato Glaciologico Italiano* — n. 4 — 1921 — Torino.

(2) Fantoli G. — « Alcune note d'idrografia sulla estensione dei ghiacciai nel dominio dei nostri fiumi alpini, sul traffico e sul regime della acque glaciali » — *Annali della Utilizzazione delle Acque* — Vol. II — 1925.

(3) Gherardelli L. — « Il dominio glaciale della Valle d'Aosta e sua influenza sul regime dei deflussi » — Ministero dei Lavori Pubblici — Ufficio Idrografico del Po — Roma — 1931.

(4) Alfieri S. — « Deflussi glaciali e loro influenza sul regime della Dora Baltea » — Comitato per l'Ingegneria del Consiglio Nazionale delle Ricerche — Roma — 1933.

(5) idem — « Caratteri idrologici dei maggiori corsi d'acqua piemontesi ed influenze dei ghiacciai sui deflussi » — *Bollettino Comitato Glaciologico*, n. 17 — 1937 — Torino.

(6) Baronio G. — « Indagini sul ghiacciaio dei Forni » — *Bollettino Comitato Glaciologico* — n. 13 — 1933 — Torino.

(7) Visentini M. — « Indagini idrografiche al ghiacciaio dei Forni Relazione sullo stato delle ricerche alla fine del 1937 » — *Bollettino Comitato Glaciologico*, n. 18 — 1938 — Torino.

(8) Monterin U. — « Ricerche sull'ablazione e sul deflusso glaciale sul versante meridionale del Monte Rosa » — *Bollettino Comitato Glaciologico Italiano*, n. 11 — 1931.

(9) idem — « Ricerche sul contributo delle condensazioni occulte nei deflussi dei torrenti alpini » (Osservatori di Meteorologia e Geofisica del Monte Rosa) — *Bollettino del Comitato Glaciologico*, n. 19 — 1939 — Torino.

(10) Merla G. — « Nuove indagini al Ghiacciaio dei Forni » — *Annali dei Lavori Pubblici* — Dicembre 1937.

(11) Pantanelli E. — « Evaporazione e condensazione sul terreno » — Atti XXII Riunione della Società per il progresso delle scienze — Bari — 1933.

(12) Sensidoni F. — « Contributo al problema idrico nelle regioni costiere a clima caldo arido » — Giornale del Genio Civile — 1945.

EVALUATION OF DEW AMOUNTS

LLOYD L. HARROLD AND F. R. DREIBELBIS

SUMMARY

The automatic print-weigh mechanism on the lysimeters at the U. S. Department of Agriculture, Soil and Water Conservation Research Division Station at Coshocton, Ohio provides data from which the daily amounts of dew have been calculated. These 0.002-acre natural soil blocks of 8-foot depth are delicately balanced on scales having a 5-pound sensitivity. The consistent gains in weight during periods of no rainfall were transcribed into figures that represent the amount of dew for each day. Two weighing lysimeters are cropped to a rotation of corn, wheat, and legume-grass meadow. One is in continuous cover of legumes and grass.

The largest amount of dew in a single day amounted to 0.08 inch of water. The greatest monthly total was 1.39 inches in August 1951. In a year, the total amount of condensation and absorption often exceeded 10 inches of water.

Condensation and absorption on a dry soil was greater than that on a moist soil. This daily value on the dry soil was 0.05 inch and on the moist soil, 0.004 inch for a period of several days in August 1953.

Dew is an important source of water in agriculture. This fact has long been recognized in many parts of the world. In the arid areas however, the value of dew has been most noticeable. Vegetation has developed in these dry areas where neither rain nor ground water is enough to account for its growth. Went (1955), in the 1955 Year Book of Agriculture, reports that the dew contributes much towards meeting the water requirements of vegetation. In the growing season, dew is of considerable value to agriculture, even though evaporation in the morning hours usually vaporizes as much or more water than the amount of dew condensed during the previous afternoon and evening. Several investigators have made estimates of the amount of dew using climatological observations. Actual measurements of dew beside those on the Coshocton, Ohio lysimeters as described below, are very few.

DESCRIPTION OF THE COSHOCTON LYSIMETERS

Perhaps the most recent and accurate measurements of dew to date were made on the weighing lysimeters of the Soil and Water Conservation Research Division Station near Coshocton, Ohio. These lysimeters as described by Harrold and Dreibelbis (1951) have supplied data on evapotranspiration, condensation, runoff, and percolation continuously since 1944. Briefly, the lysimeters are natural soil monoliths 8 feet deep and 0.002 acre in surface area (6.22 × 14-foot rectangle). These soil monoliths are encased in concrete side walls with steel bottoms. The bottom plate is perforated to allow percolating water to pass freely to the measuring tanks. The soils belong to the Gray Brown Podzolic group and are residual in origin. They were derived from shale at two of the locations, and of sandstone at the third. On the Muskingum silt loam the texture below A horizon which is 7 inches deep becomes lighter with depth. The bottom 3 feet of the 8-foot profile consists of undecomposed bedrock. The Keene silt loam below the A horizon grades into a silty clay loam and the lowest 3 feet is clay shale. There are eleven lysimeters at this watershed-hydrology research station. All are equipped to measure surface runoff and percolation. Seven are cropped in a rotation of corn, wheat, and meadow. Four are in permanent pasture grass. All are within fields cropped the same as the lysimeters.

The weighing mechanism which provides data from which evapotranspiration and dew can be calculated, is unique. Two cropped and one grass lysimeter are equipped with scales which automatically record a weight figure every 10 minutes. Total weight of soil, water, concrete, and steel is about 65 tons. Weight differences obtained from these records, adjusted for precipitation, runoff, or percolation, represent changes in the soil block. Crop weight increases are so small, as compared to moisture changes, that thet can be neglected in computing net moisture changes. The scales are accurate to within 5 pounds or an equivalent to 0.01 inch water.

Records of dew

Ten-minute weight records for the three lysimeters averaged by hours were used to derive values of hourly changes in moisture on the 0.002-acre area. Table 1 gives a sample of the hourly values for a period of relatively heavy dew for this locality. On this date, August 17, 1951, the records showed that the meadow lysimeter gained weight consistently from midnight to 4 A.M. and from 2 P.M. to midnight. The latter was the period of greatest dew. The total for this date was 0.08 inch.

TABLE 1

Sample of detail hourly weight and moisture changes in meadow lysimeter Y103A, August 17, 1951

Time	Hourly weight (1)	Moisture change (2)	Time	Hourly weight	Moisture change
	Pounds	Inch		Pounds	Inch
Midnight	145.0	—	Noon	111.2	—
1 a.m.	147.0	0.009	1 p.m.	104.8	—.014
2	147.3	.001	2	94.8	—.022
3	148.8	.003	3	99.8	.011
4	150.7	.004	4	104.2	.010
5	150.7	0	5	107.3	.007
6	151.0	.001	6	110.0	.006
7	138.5	—.028	7	113.2	.007
8	131.0	—.016	8	116.2	.007
9	122.3	—.019	9	118.3	.005
10	122.0	—.001	10	121.0	.006
11	114.8	—.016	11	121.8	.002
12	111.2	—.008	12	124.5	.005
			24 hours	—	+ .084 — .124

(1) Average of six 10-minute weight recordings. A large constant tare weight has been subtracted from the total to obtain these weight figures.

(2) Obtained by dividing the weight difference for the hour period by 453. No rainfall, runoff, or percolation this date. All weight change is caused by moisture change—either evapotranspiration or dew.

The period of dew started at the time of rapid cooling of the air at the ground surface. It is conceivable that top leaves of tall growing vegetation were transpiring moisture while dew was condensing at the ground surface. Apparently, the temperature of this air reached dew point by 3 P.M. Air temperatures 2 inches above the ground surface on August 17 dropped 8 degrees between 2 and 3 P.M. and another 6 degrees between 3 and 4 P.M. The air temperature a foot or so above the ground may have had a saturation deficit at the time the air temperature at the ground surface was at dew point. The lysimeter weight-change record can not separate these two simultaneous processes. Its records can only be used to evaluate the net change in moisture. Dew values, if they could have been evaluated separate from concurrent transpiration might be larger than those reported herein. The values in this paper may, therefore, be considered conservative. Dew values in Table 1 were not confounded by the possiqility of concurrent transpiration because hay cutting on August 8, left only stubble.

TABLE 2

Monthly dew (1) *values for lysimeter Y103A, 1944-55*

Month	Average	Range	
	Inches	Inches	Inches
January	—	—	0.73
February	—	—	.88
March	—	1.41	.56
April	0.78	1.30	.26
May	.49	.85	.17
June	.49	.82	.17
July	.49	1.00	.07
August	.55	1.39	.07
September	.75	1.24	.20
October	.88	1.56	.45
November	.87	1.22	.39
December	—	—	.82

(1) Unaffected by drifting snow.

Average values of measured dew on lysimeter Y103A (Table 2) were lower in the growing season than in the dormant season. In the growing season, transpiration may be compensating for some of the dew, as discussed above. Maximum monthly values of dew were less than 1 inch in May and June. In other months, they ranged from 1 to slightly over 1.5 inches. Whenever drifting snow affected the weight record, it was not possible to derive a true value of condensation. For these months, dew values were omitted from Table 2. Minimum amounts of monthly condensation were also low in the growing and high in the dormant season. They ranged from less than 0.1 inch in the former to nearly 0.9 in the latter period.

The largest monthly value of summer dew was 1.39 inches. It was observed in August 1951 on lysimeter Y103A (Table 3). The crop of clover-timothy hay had been cut and removed on August 8. Only a sparse stubble cover remained on the surface for the remainder of the month. Transpiration must have been practically nil in this

period. Condensation values (Table 3) for the period are assumed to represent true dew values—as close as can be measured. The largest amount occurred on August 17. Hourly changes of moisture on this lysimeter for this date appear in Table 1 and were discussed earlier in this paper. This month was noted for its hot sunny days and cool cloudless nights. The average daily range between maximum and minimum air temperature 2 inches above the ground was 31 degrees Fahrenheit.

TABLE 3

Daily Values of DEW (CA) for August 1951 on Lysimeter Y103A

Date	DEW	Date	DEW	Date	Date
	Inches		Inches		Inches
1	0.02	12	0.06	23	0.06
2	.03	13	.07	24	.06
3	.01	14	.06	25	.06
4	.02	15	.05	26	.05
5	.03	16	.05	27	.03
6	.01	17	.08	28	.04
7	.01	18	.05	29	.05
8	.04	19	.06	30	.06
9	.05	20	.05	31	.02
10	.04	21	.05		
11	.06	22	.06	Total	1.39

A brief exploratory study was made on a bare ground plot to determine the depth of dew penetration into the soil. Gypsum fiberglas electrical resistance blocks as described by Dreibelbis and Youker (1951) were placed at the 1/2, 1½, and 2½ inch soil depths. Observations were made in triplicate at about 7 P.M., and at 6 A.M., over a period of 34 days in September and October 1951. Moisture changes of each soil block between each pair of observations were computed and compared with the total gains in weight from a lysimeter for this same period. Average results for the 34-day period appear in Table 4. They show that nearly all the absorption of dew into the soil occurred in the surface inch. Practically none penetrated to the soil-moisture measuring blocks at the 1½-inch depth or greater. These data also show the fairly close agreement between the values of dew gaged by the moisture blocks and those from the weighing lysimiters.

The daily increase in weight of the lysimeter can be attributed to condensation of moisture from outside the soil block. Diurnal fluctuations of soil tempartture probably cause some condensation of vapor within the soil pores. This has not contributed to the lysimeter weight increases.

Condensation on an area of dry soil was greater than that on a moist-soil area. This is illustrated in figure 1 which shows hourly moisture changes in irrigated lysimeter Y102C and unirrigated Y103A. Both lysimeters on August 24, 1953 were in comparable dry conditions. Dew on Y102C was 0.022 inch and that on Y103A was 0.028 inch. Y102C was irrigated on August 25. Instrument failure prevented dew determination on August 26, and 27. However, dew values for August 28, and 29, were available and they show marked differences between the two lysimeters.

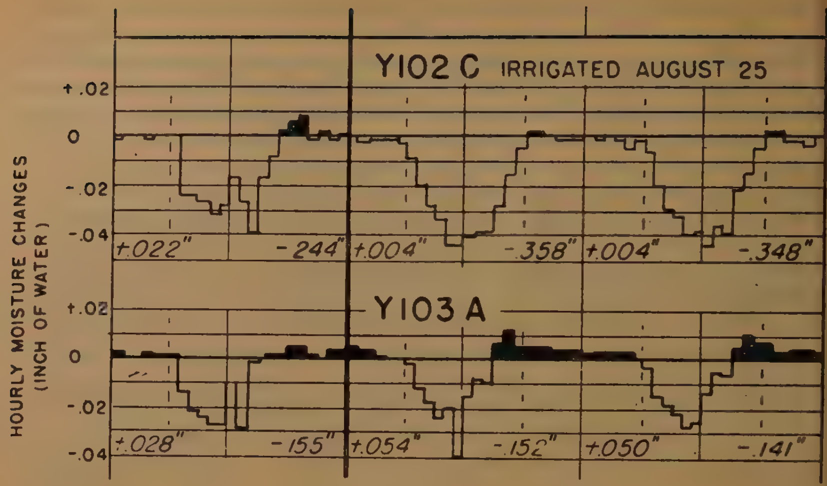


Fig. 1

On the moist, irrigated lysimeter Y102C, dew averaged only 0.004 inch for these 2 days. That on the dry lysimeter Y103A averaged 0.052 for the same period—13 times as much.

TABLE 4

Average daily moisture condensation absorbed by bare soil and dew evaluations on lysimeter Y102C, September 22 — October 26, 1951

Evaluations		Condensation
		Inch per day
Lysimeter		0.015
Soil-moisture blocks at depth of:		
½ inch		.011
1-½ inches	Less than	.001
2-½ inches	Less than	.001

The lysimeter records may help answer the question that some have concerning the value of this dew to vegetation or for other uses. There is a feeling that the condensed moisture is lost by evaporation in the morning sunshine and consequently may not be beneficial. It is common knowledge that grass, trees, and other vegetation wet with the evening's dew usually are dry by 10 or 11 o'clock the next morning. Weight records revealed the fact that the vegetation extracted very little moisture from the soil during the periods of dew evaporation. Apparently, there are times when dew is of considerable value to vegetation and to soil moisture.

Discussion

Went (1955) in the Year Book of Agriculture on Water reported that in some areas of the world dew is recognized as an important source of water for crops. Investigators found that dew is absorbed by the leaves of the vegetation. Furthermore, accumulation of dew on leaves often resulted in flow of water down the stalk and into the ground. Thus noticeable additions to soil moisture have occurred. This was observed at the Coshocton Station—especially in August 1951. Although our corn crop received only 0.75 inch of rain that month, it did not wilt. That was unusual. We noticed, however, that the soil around the base of the corn plant was moist from dew flow nearly every morning that month. Enough dew occurred to sustain crop growth. Lysimeter records (Table 3) showed that there was 1.39 inches of dew that month.

The Coshocton lysimeters evaluated the magnitude of dew to be as high as 10 inches of water in some years. As much as 20 percent of the total water supply came in the form of dew. Eighty percent was precipitation—rain and snow. From the amount of heat exchange, one can calculate the amount of dew that can be deposited. Went, in the 1955 Year Book of Agriculture, reports that the maximum amount of dew for a year under ideal conditions could be about 15 inches of water. The Coshocton lysimeter evaluations appear to be in agreement with the theoretical estimate.

Acknowledgment

This Soil and Water Conservation Research Division Station is maintained by Agricultural Research Service, U.S. Department of Agriculture in cooperation with the Ohio Agricultural Experiment Station, Wooster, Ohio.

REFERENCES

Dreibelbis, F. R. and Youker, R. E. An improved soil-moisture measuring unit, *Trans. Amer. Geophys., Union* 32, 447-449. 1951.

Harbold, L. L. and Dreibelbis, F. R. Agricultural Hydrology as evaluated by monolith lysimeters, U. S. Dept. Agri., 1951.

Went, F. W., Fog, mist, dew and other sources of water. U.S.D.A. *Year Book of Agriculture*, 1955.

DIFFUSION DE L'EAU A L'ÉTAT VAPEUR ET LIQUIDE AU VOISINAGE DE LA SURFACE D'ÉVAPORATION ET DÉSSECHEMENT SUPERFICIEL DU SOL

M. HALLAIRE

Station de Bioclimatologie de Versailles, Institut National de la Recherche agronomique FRANCE

RÉSUMÉ

Si l'on soumet la surface d'une colonne de terre à une évaporation E (mm/*j*), cette dernière représente le débit total à la surface même du sol tandis que le débit dQ/dt à une profondeur z s'obtient en corrigeant E des pertes en eau du sol entre les niveaux o et z.

On peut alors vérifier qu'entre les débits dQ/dt aux différentes profondeurs et les gradients d'humidité dH/dz correspondants, existe à tout moment une relation de la forme :

$$\frac{dQ}{dt} = A\frac{dH}{dz} + B \quad \text{A et B = Ctes à un même moment.}$$

Pour expliquer ce résultat, on a été amené à admettre que le débit total en surface, E, était la somme des deux termes B et Δ :

B est le débit assuré par le déplacement d'ensemble d'un film liquide de la profondeur jusqu'à la surface où se produit l'évaporation;

Quant à Δ, tout se passe comme s'il correspondait à la diffusion d'une masse d'eau-vapeur provenant de l'évaporation dans la masse même du sol.

Si l'on désigne par Y (mm par jour et par tranche de 1 cm), cette évaporation apparente dans la masse, elle varie avec la profondeur z selon la loi exponentielle : $Y = Y_s \exp(-z/a)$. Il en résulte que la composante $\Delta = \int Y dz$ de l'évaporation contribue pour une part importante au dessèchement des horizons très superficiels du sol et à la formation naturelle du mulch qui freine l'évaporation. En outre, les quantités d'eau perdues, lorsqu'apparait ce mulch dépendent essentiellement de la part relative du débit vapeur Δ/E.

I — GENERALITES SUR LA DIFFUSION CAPILLAIRE DE L'EAU DANS LE SOL

On admet que le taux de diffusion de l'eau dans le sol selon une direction z'z est donné par la formule :

$$\frac{dQ}{dt} = \frac{d\Phi}{d.z} \qquad (1)$$

où dQ/dt désigne le débit (exprimé par exemple en mm/jour), où Φ est la somme des potentiels auxquels l'eau se trouve soumise (potentiel capillaire ψ potentiel dû à la pression hydrostatique Φ_1, potentiel dû à la pesanteur Φ_2) et où λ représente le coefficient de conductibilité du sol pour l'eau. Ce dernier dépend du nombre et de la dimension des canaux qui, pleins d'eau, peuvent en assurer le transport; il décroît ainsi très rapidement, pour un même sol, à mesure que l'humidité diminue ou, ce qui revient au même, à mesure que le potentiel ψ s'accroît.

En sol ressuyé, l'humidité étant inférieure à la capacité de rétention, le gradient du potentiel ψ est normalement très supérieur au gradient de $(\Phi_1 + \Phi_2)$; la formule (1) peut alors se ramener à :

$$\frac{dQ}{dt} = \lambda(\psi)\frac{d\psi}{dz} \qquad (2)$$

Cette simplification est également justifiable dans le cas où l'eau se déplace horizontalement.

Il est enfin commode d'exprimer le taux de diffusion en fonction du gradient d'humidité dH/dz où H, quantité d'eau contenue dans 100 g de terre sèche, est directement mesurable. D'où la transformation classique :

$$\frac{dQ}{dt} = \lambda(\psi)\frac{d\psi}{dH}\frac{dH}{dz}$$

soit :

$$\frac{dQ}{dt} = \Lambda \frac{dH}{dz} \quad \text{avec } \Lambda = \lambda(\psi)\frac{d\psi}{dH} \tag{3}$$

Λ est donc le produit de λ, fonction décroissante, par $d\psi/dH$ qui est fonction croissante de ψ, comme le montrent les courbes (ψ — H) relatives à n'importe quel sol. C'est pourquoi certains auteurs ont pensé que Λ était constant pour un même sol tandis que d'autres n'observaient qu'une décroissance assez faible de Λ avec le taux d'humidité H, tout au moins à l'intérieur de la gamme d'humidités : point de flétrissement permanent — capacité de rétention.

Dans l'étude expérimentale de la diffusion capillaire, beaucoup d'auteurs ont examiné le déplacement de l'eau dans un sol sec à partir d'une masse d'eau libre; d'autres faisaient circuler dans une colonne de terre, de l'eau soumise aux extrémités à une dépression différente; d'autres encore recherchaient les conditions de circulation de l'eau depuis une zone humide vers une zone plus sèche à l'intérieur d'une terre située dans un récipient hermétiquement clos.

Nous craignons que ces recherches ne fournissent que des réponses incomplètes à un important problème qui préoccupe l'agronome comme l'hydrologiste : celui de l'évaporation ou de la transpiration végétale. Dans les conditions naturelles c'est en effet l'évapotranspiration qui provoque le déplacement de l'eau jusqu'à la surface ou jusqu'à la zone active du système radiculaire. Responsable de la diffusion capillaire, l'évapotranspiration peut en contre partie, se trouver limitée par la lenteur des déplacements de l'eau lorsque le sol a atteint un certain degré de secheresse; c'est ainsi que le flétrissement des végétaux est dû au fait que l'eau ne peut diffuser à une vitesse suffisante dans les couches desséchées où se trouvent les racines. En outre, dans les conditions d'alimentation normale du vegetal, l'eau ne provient généralement pas de la nappe phréatique qui, lorsqu'elle est située à plus de 1m,50 ou 2m de profondeur, ne joue qu'un rôle minime dans l'approvisionnement des plantes. Elle provient du desséchement même du sol dans lequel elle circule.

Ces remarques nous ont conduit à envisager le mouvement de l'eau dans des colonnes de terre dont l'humidité initiale Ho était la même à tous les niveaux, voisine de la capacité de rétention, et dont on soumettait la tranche supérieure à une évaporation plus ou moins intense E.

L'évaporation E, exprimée en mm/jour, n'est autre que le débit en surface $\left(\frac{dQ}{dt}\right)_s$. Quant au débit dQ/dt à une profondeur quelconque z on peut l'obtenir en retranchant de E (mm/jour) la quantité d'eau, exprimée dans le même système d'unités, cédée par la tranche de terre o — z lors de son dèssèchement.

Les considérations précédentes et en particulier la formule (3) laisseraierit penser que si les débits dQ/dt, ainsi mesurés à un même moment de la surface vers la profondeur, sont portés sur un graphique en fonction des gradients d'humidité dH/dz correspondants, la série de points obtenus doit se répartir sur une courbe continue

du type de celles représentées Fig. I : droite D issue de l'origine si Λ est indépendant du taux d'humidité, courbe C issue de l'origine mais tournant sa concavité vers dH/dz croissants si Λ diminue avec le taux d'humidité H.

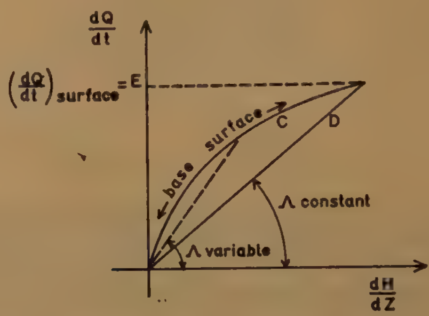


Fig. 1 — Relation supposée entre le débit dQ/dt et le gradient dH/dz.

Examinons à présent la variation réelle du débit dQ/dt en fonction du gradient d'humidité dH/dz.

II. Etude experimentale

a) *Relation entre le débit et le gradient d'humidité*

Une série de colonnes de terre, préparées de façon identique [1], sont soumises à une même évaporation E. Celle-ci peut être mesurée directement pendant un intervalle de temps Δ t :

$$E = \frac{\Delta P}{S \Delta t} \text{ (mm/jour)} \tag{4}$$

ΔP représentant la variation de poids en dg de la colonne de terre, S la surface évaporante en cm² et Δt l'intervalle de temps en jours.

Par ailleurs, en sacrifiant lors de chaque pesée une ou deux colonnes de terre pour déterminer par la méthode directe l'humidité des tranches successives, on peut évaluer le débit aux différentes profondeurs : si $(\Delta H)_1$ est la variation d'humidité de la tranche supérieure, d'épaisseur z_1, la quantité d'eau cédée par cette dernière est :

$$q = \frac{\sigma}{10} z_1 (\Delta H)_1 \text{ (mm)} \qquad (\sigma = \text{densité apparente du sol})$$

Le débit à la profondeur z_1 sera donc :

$$\left(\frac{dQ}{dt}\right)_1 = E - \frac{\sigma}{10} \frac{z_1 (\Delta H)_1}{\Delta t} \text{ (mm/jour)} \tag{5}$$

Opérant ainsi de proche en proche pour les tranches sussessives, on obtient le débit à des profondeurs de plus en plus grandes. Il convient toutefois de souligner que l'erreur affectant dQ/dt va croissant.

[1] Les colonnes de terre étaient, soit prélevées à l'emporte-pièce en plein champ dans des tubes d'acier de 7 cm de diamètre et de 30 cm maximum de long, soit reconstituées dans des tubes à partir d'une terre humide et émiettée. Cette deuxième méthode permettait de réaliser des colonnes plus longues et de contrôler plus sûrement le degré de tassement.

Le gradient d'humidité peut être évalué, aux niveaux de séparation des tranches de sol considérées, à partir des mesures d'humidité précitées. On est ainsi en mesure de représenter la variation, à un même moment, de dQ/dt en fonction de dH/dz.

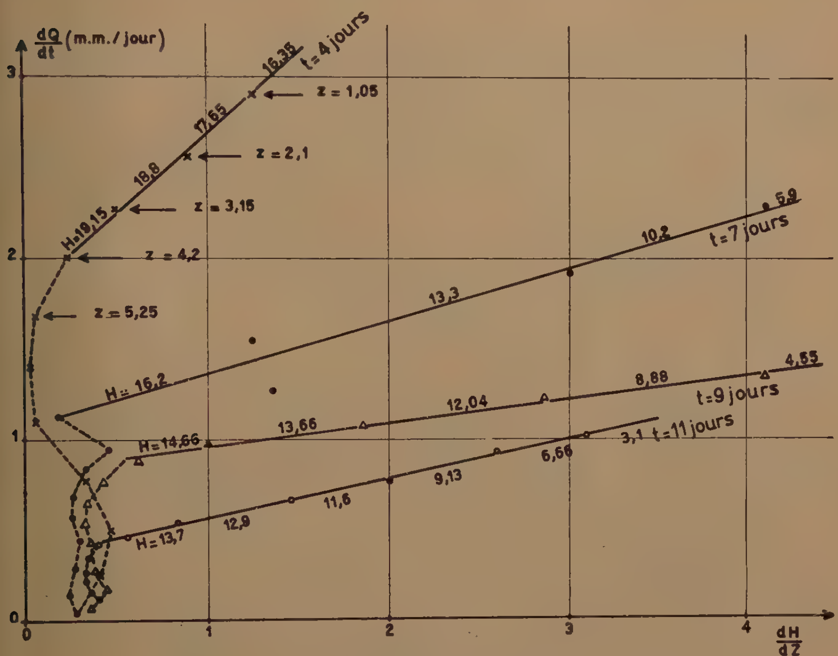


Fig. II — Relation réelle entre dQ/dt et dH/dz.

Les courbes trouvées (Fig. II) diffèrent considérablement du résultat attendu (Fig. I). On observe en effet deux parties distinctes : une première correspondant aux horizons superficiels présente une forme remarquablement linéaire répondant à l'équation :

$$\frac{dQ}{dt} = A(t)\frac{dH}{dz} + B \qquad (6) \qquad \left\{ \begin{array}{l} \text{A et B Ctes à un moment donné} \\ \text{A fonction décroissante du temps } t \end{array} \right.$$

tandis qu'aux profondeurs supérieures, la courbe, beaucoup moins régulière, exprimerait que dH/dz est à peu près constant, indépendent par conséquent du débit dQ/dt.

b) *Etude du desséchement en profondeur sous l'effet d'une évaporation en surface.*

Pour être à même de mieux comprendre et d'interpréter le mécanisme du déplacement de l'eau qui conduit à la relation trouvée entre le débit et le gradient d'humidité, il est utile d'observer comment se répartissent dans la profondeur du sol les pertes en eau qui compensent l'évaporation.

Des colonnes de terre qui au temps $t = 0$ presentaient la même humidité H_o (H_o = capacité de rétention soit environ 25 pour le limon étudié ici) sont soumises à une évaporation E.

Les pertes totales du temps o au temps t sont données (en m.m) par :

$$\int_o^t \mathrm{Edt} = \frac{\Delta P}{S} \qquad (7)$$

a variation de poids ΔP et la surface S étant évaluées respectivement en dg et en cm^2

Un dosage de l'humidité tranche par tranche permet alors d'évaluer la variation d'humidité $\Delta H = Ho - H$ à chaque niveau.

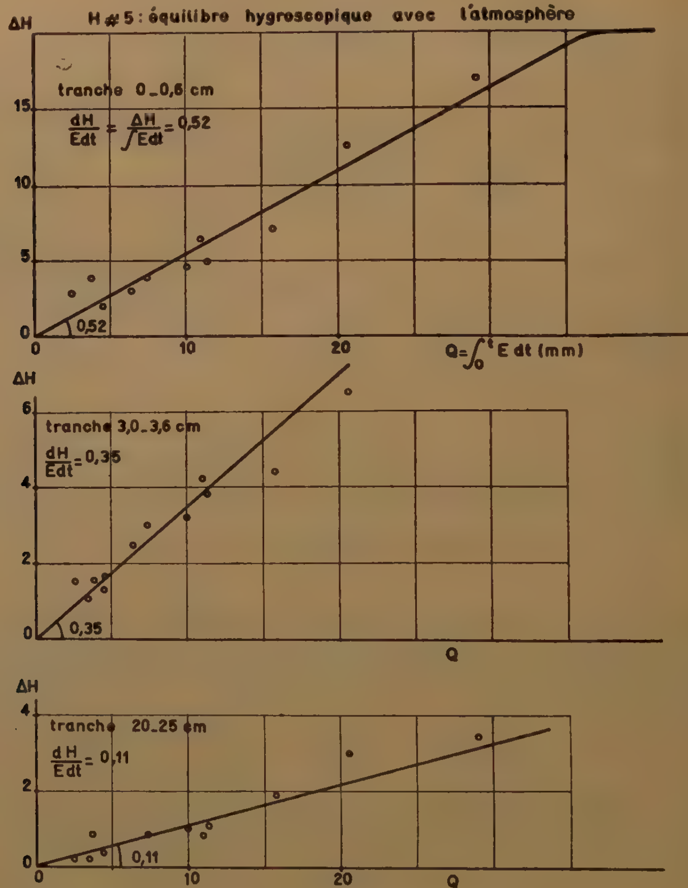


Fig. III — Abaissement d'humidité en profondeur en fonction de la quantité d'eau perdue par évaporation.

Les graphiques de la fig. III sont relatifs à une série d'expériences réalisée sur le limon de Versailles, à la densité 1,5, le taux d'évaporation ne dépassant pas 2 mm par jour. Ils mettent en évidence une relation de proportionnalité entre ΔH à un niveau quelconque et la perte totale en eau $\int^t \mathrm{Edt}$:

$$\Delta H = \rho\,(z) \int_o^t \mathrm{Edt} \qquad (8)$$

c'est à dire en différentiant par rapport au temps t :

$$\frac{dH}{dt} = \rho\,(z)\,E \qquad (9)$$

Bien entendu cette relation n'est plus valable au bout d'un certain temps. Lorsque l'humidité en surface H_s atteint une valeur telle qu'il y ait équilibre d'hygroscopicité avec l'air ($Hs = 4$ à 6 dans le cas présent), elle cesse de décroître et ΔHs se maintient alors constant.

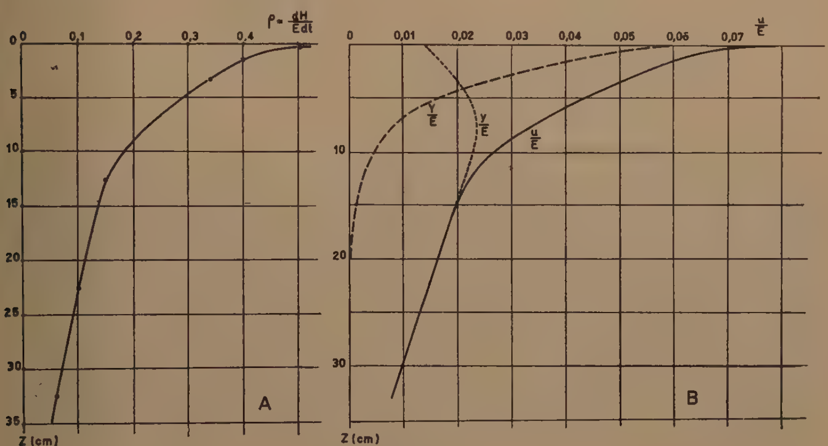


Fig. IV

La courbe de variation de $\rho = dH/Edt$ en fonction de z est représentée fig. (IV A) A peu près linéaire en profondeur, elle offre au contraire au voisinage de la surface l'allure d'une exponentielle.

Il suffit d'opérer sur ρ une légère transformation pour exprimer la quantité d'eau cédée par unité de temps et par tranche de 1 cm. Cette quantité d'eau que l'on désignera par u est :

$$u = \frac{\rho}{10}\,\frac{dH}{dt}$$

c'est à dire en tenant compte de (9) :

$$u = \frac{\sigma}{10}\,\rho\,E \qquad (10)$$

La courbe représentée fig. IV B montre la variation de u/E avec la profondeur.

Remarquons enfin que les profils hydriques H (z) présenteront une forme analogue à la courbe ρ (z) mais retournée et plus ou moins dilatée selon la valeur des pertes totales $\int^t \mathrm{Edt}$ (voir fig. V). En effet l'équation (8) peut s'écrire :

$$Ho - H = \rho\,(z) \int^t \mathrm{Edt} \qquad \text{soit } H = Ho - \rho\,(z) \int^t \mathrm{Edt}$$

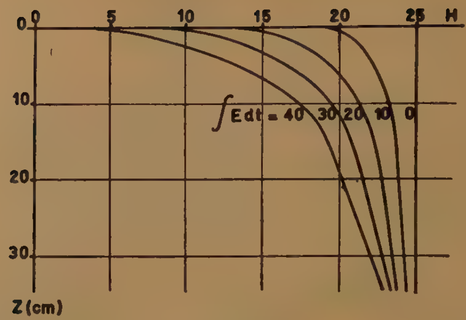


Fig. V

Ainsi les profils hydriques fig. V présentent-ils une forte concavité près de la surface tandis qu'ils sont à peu près linéaires en profondeur. On retrouve ici ce résultat observé fig. II d'un gradient dH/dz indépendant de la profondeur au-delà d'un certain niveau.

Enfin, il est possible en partant des valeurs expérimentales de ρ au voisinage de la surface de retrouver la relation (6) entre le débit et le gradient d'humidité. Les calculs sont explicités dans le tableau suivant :

Profondeur z (cm)	$\rho = \frac{dH}{Edt}$	H au temps t	$\frac{dH}{dz}$	$\frac{Qd}{dt}$ (mm/jour)
0 — 0,6	0,5	$Ho - 0{,}5 \int Edt$	$0{,}1 \int Edt$	0,955 E
0,6 — 1,2	0,44	$Ho - 0{,}44 \int Edt$	$0{,}067 \int Edt$	0,915 E
1,2 — 1,8	0,4	$Ho - 0{,}4 \int Edt$	$0{,}05 \int Edt$	0,879 E
1,8 — 2,4	0,37	$Ho - 0{,}37 \int Edt$	$0{,}033 \int Edt$	0,836 E
2,4 — 3	0,35	$Ho - 0{,}35 \int Edt$	$0{,}025 \int Edt$	0,805 E
3 — 3,6	0,32	$Ho - 0{,}335 \int Edt$		
$z = 15$ H	$- 0{,}005z$		0,005 Edt	décroît avec z

On peut alors vérifier graphiquement (fig. VI) qu'au voisinage de la surface dQ/dt est lié à dH/dz par la relation :

$$\frac{dQ}{dt} = \frac{2\,E}{\int Edt} \frac{dH}{dz} + 0{,}78\,E \qquad (10)$$

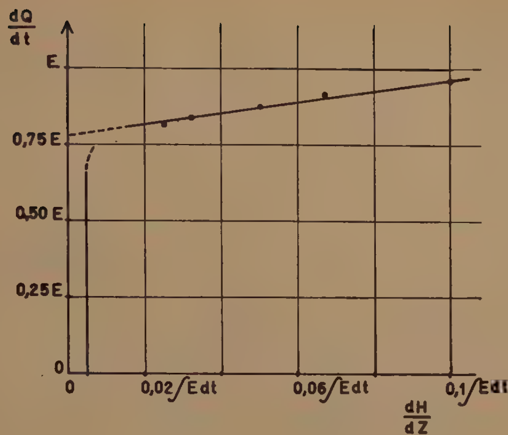


Fig. VI

qui est bien de la forme trouvée précédemment (équation 6) puisque le terme figurant devant dH/dz est une constante mais décroît normalement avec le temps.

Remarque : Il est important de rappeler que ces derniers résultats qui conduisent notamment à une valeur de B = 0,78 E ne s'appliquent qu'à une série d'expériences réalisées sur le limon de Versailles, à la densité 1,5 et où l'évaporation n'excédait pas 2 mm par jour.

En opérant soit avec un autre sol, soit avec la même terre mais à une densité différente ou encore en imposant des évaporations supérieures on aboutit toujours à une courbe (dQ/dt, dH/dz) qui offre les deux parties distinctes mises en évidence fig. II et VI .Toutefois le rapport B/E peut être extrêmement variable. On peut entre autre vérifier (fig. VII) qui, se l'on fait croître l'évaporation, le terme B ne peut

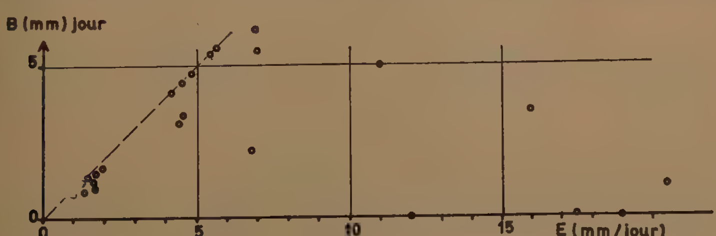


Fig. VII

excéder une valeur de l'ordre de 3 à 5 mm/jour; le rapport B/E devient ainsi plus faible et peut même atteindre 0 pour des évaporations très intenses.

III — Interpretation des resultats

Les considérations exposées plus haut sur la diffusion liquide amenaient à prévoir une relation entre le débit et le gradient d'humidité du type de celles représentées par les courbes C ou D (fig. I). La relation trouvée expérimentalement (fig. II et VI

et équations 6 et 10) ne semblent donc pouvoir correspondre à une simple diffusion liquide. Elle suggère en outre que le mouvement de l'eau jusqu'en surface met en cause deux phénomènes distincts, l'un conduisant à la relation linéaire entre le débit et le gradient d'humidité dans les horizons superficiels, l'autre commandant les mouvements de l'eau en profondeur et conduisant à ce gradient d'humidité approximativement constant à un moment donné.

a) *La relation* dH/dz = *constante en profondeur et le déplacement d'un film d'eau continue.*

Considérons cette partie de la courbe (fig. II et VI) qui correspond à des profondeurs supérieures à 5 ou 10 cm et où le gradient d'humidité $d\mathrm{H}/dz$, croissant dans le temps apparaît pratiquement indépendant de la profondeur, indépendant par conséquent à un moment donné du débit $d\mathrm{Q}/dt$.

Ce résultat est contraire à ce que laissait prévoir la relation (3). En effet, selon cette loi, le gradient $d\mathrm{H}/dz = (1/\Lambda)\ d\mathrm{Q}/dt$ devrait, à une époque t donnée, décroître avec la profondeur d'une part parce que le débit décroît lui-même, d'autre part parce que l'humidité H augmente avec z et que le terme $1/\Lambda$ doit ainsi diminuer.

En outre l'expérience montrait qu'un niveau donné z se laisse traverser, sous l'effet d'une évaporation constante, par un débit constant dans le temps, tandis que $d\mathrm{H}/dz$ augmente. On peut noter en particulier en début d'expérience ce résultat étonnant de l'existence d'un débit à chaque niveau alors que le gradient d'humidité est nul.

Pour expliquer ces anomalies apparentes, on remarquera tout d'abord que la relation (3) $d\mathrm{Q}/dt = \Lambda\ d\mathrm{H}/dz$ n'est qu'une forme modifiée de la véritable formule de diffusion (1) $d\mathrm{Q}/dt = \lambda\ d\psi/dz$. Mais la transformation classique qui permet de passer de (1) à (3) n'est justifiable que si à toute valeur de H correspond une seule valeur du potentiel capillaire ψ et inversement. Or on sait que les méthodes de détermination de ψ en fonction de l'humidité font apparaître deux courbes distinctes $\psi_s(\mathrm{H})$ et $\psi_h(\mathrm{H})$ suivant que l'équilibre est réalisé à la suite d'un dessèchement ou d'une réhumectation du sol (fig. VIII). C'est le phénomène bien connu d'hystérésis de la courbe potentiel capillaire — humidité.

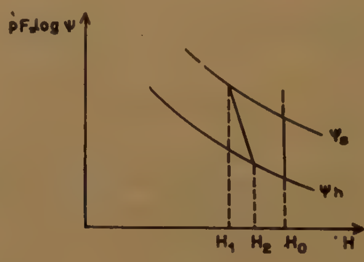


Fig. VIII

Imaginons alors une colonne de terre présentant une humidité initiale H*o*. Pour que l'eau se déplace vers la surface d'évaporation, il faut qu'elle soit soumise à une tension. Si par ailleurs le débit diminue avec la profondeur, il est évident que cette tension s'exerçant sur l'eau décroîtra elle-même avec la profondeur z. Mais cette tension n'est autre, numériquement du moins, que le potentiel capillaire ψ.

Le potentiel capillaire ψ doit obligatoirement décroître avec z. Or en début d'expérience l'humidité est la même à tous les niveaux. Ce résultat ne peut s'expliquer

que par l'hystérésis observé sur les courbes ψ (H). Il faut donc admettre que selon la profondeur, selon en d'autres termes la rapidité de desséchement, le potentiel capillaire varie entre les limites ψ_s (Ho) et ψ_h (Ho). De même au bout d'un temps t où l'humidité se trouve comprise entre H_1 et H_2, le potentiel capillaire s'étagera entre ψ_s (H_1) et ψ_n (H_2). (fig. VIII).

Ce phénomène d'une tension ou d'un potentiel capillaire décroissant régulièrement avec la distance, indépendamment du taux d'humidité, ne peut se concevoir que si la tension est transmise le long d'un film d'eau continu grâce aux forces de cohésion de l'eau (forces de Van der WAALS). Quant au gradient d'humidité observé au bout d'un certain temps on ne doit pas le considérer comme l'élément moteur de l'eau mais comme la simple conséquence d'un mouvement d'ensemble qui provoque un desséchement d'autant moins intense que la profondeur est plus grande.

b) *La relation* dQ/dt = A dH/dz + B *au voisinage de la surface*

Comparée à la loi de diffusion attendue : $dQ/dt = \Lambda\, dH/dz$, cette relation ne semblerait pouvoir traduire une diffusion liquide, d'une part parce que le terme A varie avec le temps et non avec le taux d'humidité, d'autre part en raison du terme constant B.

1/ *l'hypothèse de la superposition d'un débit liquide B et d'un débit vapeur* $\Delta = E - B$.

La relation expérimentale (6) entre le débit et le gradient d'humidité peut s'expliquer si l'on admet que le terme B correspond au débit assuré en surface par le déplacement du film liquide venant de la profondeur tandis que les strates superficiels se dessécheraient sous l'effet d'une évaporation directe dans la masse fournissant en surface un débit vapeur $\Delta_s = E - B$.

Admettons en effet que l'atmosphère lacunaire du sol présente aux faibles profondeurs un déficit de saturation de la vapeur. Il s'ensuivra une évaporation dans la masse :

$$Y = M\,[F(t) - f] \qquad \text{mm/jour/tranche de 1 cm} \tag{11}$$

où M est une constante, f la tension de vapeur, F (t) la tension maximum.

La vapeur ainsi produite devra s'évacuer par diffusion selon la formule :

$$\frac{dQ}{dt} = k\,\frac{df}{dz} \ \text{(mm/jour)} \tag{12}$$

k étant le coefficient de diffusivité de la vapeur dans la masse poreuse considérée.

Un calcul simple montre alors qu'en l'absence de gradient de température, les pertes par évaporation Y varient avec la profondeur selon la loi exponentielle :

$$Y = Ys \exp(-z/a) \qquad \begin{cases} Ys = Y \text{ en surface} \\ a = \sqrt{k/M} \end{cases} \tag{13}$$

Dès lors le débit vapeur au niveau z sera :

$$\Delta = \int_z^{\infty} Y ds = aYs \exp(-z/a) \tag{14}$$

ou encore

$$\Delta = aY$$

En surface il aura la valeur :

$$\Delta = a\mathrm{Y}s \tag{15}$$

le débit à la profondeur z peut donc finalement s'écrire :

$$\Delta = \Delta_s \exp(-z/a) \tag{16}$$

Quant au déficit de saturation il variera lui aussi selon une loi exponentielle puisque selon (11) :

$$\mathrm{F}(t) - f = \frac{\mathrm{Y}}{\mathrm{M}} = \frac{\Delta}{a\mathrm{M}} = \frac{\Delta s \exp(z/a)}{\sqrt{k\mathrm{M}}} \tag{17}$$

Exprimons à présent le débit total (liquide et vapeur) à un niveau quelconque z. Il s'écrit :

$$\frac{d\mathrm{Q}}{dt} = \delta + \Delta = \delta + \Delta s \exp(-z/a) \tag{18}$$

δ désignant le débit liquide.

Exprimons d'autre part les pertes en eau à la profondeur z, du temps 0 ou temps t. Evaluées en mm par tranche de 1 cm, elles sont données par :

$$q = \frac{\sigma}{10}(\mathrm{H}o - \mathrm{H})$$

$$\text{et} \quad q = \int_0^t \mathrm{Y}s \exp(-z/a)\, dt - \int_0^t \frac{d\delta}{dz}\, dt$$

d'où l'on tire, en égalant et en différenciant par rapport à z :

$$\frac{\sigma\, d\mathrm{H}}{10\, dz} = \exp(-z/a) \int_0^t \mathrm{Y}s\, dt + \int_0^t \frac{d^2\delta}{dz^2}\, dt \tag{19}$$

ou enfin, si l'on élimine exp ($-z/a$) entre les équations (18) et (19) :

$$\text{(20)} \qquad \frac{d\mathrm{Q}}{dt} = \frac{a^2\sigma\, \mathrm{Y}s}{10 \int \mathrm{Y}s\, dt} \frac{d\mathrm{H}}{dz} + \mathrm{B} \text{ avec (2o') } \mathrm{B} = \delta - a^2\mathrm{Y}s \frac{\int \frac{d^2\delta}{dz^2}\, dt}{\int \mathrm{Y}s\, dt}$$

Cette relation théorique entre le débit et le gradient d'humidité est bien conforme à la relation expérimentale (6 ou 10) : le terme figurant devant $d\mathrm{H}/dz$ sera en effet fonction décroissante du temps comme il avait été trouvé expérimentalement. Quant à la condition formulée en (20'), il suffit d'admettre que le débit liquide δ est quasiment constant dans les premiers cm du sol en posant $\delta = \delta_0$, pour en déduire

$$\frac{d^2\delta}{dz^2} = \mathrm{O} \text{ et } \mathrm{B} = \delta_0$$

Ainsi la composante B de l'évaporation E correspondrait au débit assuré par le film liquide, tandis que le complément $\Delta s = \mathrm{E} - \mathrm{B}$ serait un débit vapeur en surface provenant de l'évaporation Y dans la masse du sol. (voir fig. IX.)

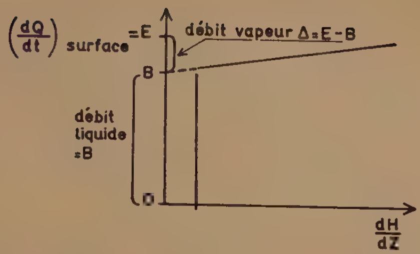


Fig. IX

2/ difficultés soulevées par la dernière hypothèse : diffusion turbulente de la vapeur dans le sol.

Comparons les deux relations théorique et expérimentale :

$$(20) \qquad \frac{dQ}{dt} = \frac{a^2\sigma \, Ys}{10 \int Ys \, dt} \frac{dH}{dz} + B \quad \text{et (10)} \quad \frac{dQ}{dt} = \frac{2\,E}{\int Edt} + 0{,}78\,E$$

L'hypothèse précédente revient donc à dire que, dans les expériences particulières qui ont conduit à l'équation (10), le débit liquide B était égal à 0,78 E tandis que le débit vapeur en surface Δs représentait le complément soit 0,22 E.

Puisque $\Delta s = aYs$, on peut en déduire :

$$Ys = \frac{0{,}22\,E}{a}$$

Cette proportionalité entre Ys et E permet d'écrire :

$$\frac{a^2\sigma \, Ys}{10 \int Ys \, dt} = \frac{a^2\sigma \, E}{10 \int Edt}$$

En identifiant d'autre part les deux équations (10) et (20) on obtient :

$$\frac{a^2\sigma \, E}{10 \int Edt} = \frac{2E}{\int Edt}$$

d'où l'on tire la valeur du coefficient $a = \sqrt{k/M.}$: $a = 3.65$

Les pertes par évaporation directe à chaque profondeur z sont alors données par :

$$Y = \frac{\Delta s}{a} \exp(-z/a) = \frac{0{,}22\,E}{3{,}65} \exp(-z/3{,}65)$$

Dès lors les pertes globales u/E représentées en fonction de la profondeur (fig. IV)) peuvent être analysées en fonction de leurs deux; composantes : Pertes Y/E dues à la diffusion vapeur et pertes y/E dues à la diffusion liquide, (voir fig. IV).

Toutefois pour que le débit vapeur dans le sol puisse atteindre 22 % de l'évaporation E, il faudrait que la diffusion vapeur ne soit pas une simple diffusion moléculaire comme le prouve le calcul suivant.

Le déficit de saturation dans le sol est en effet donné par :

$$F(t) - f = \frac{\Delta s}{\sqrt{kM}} \exp(-z/a) \tag{17}$$

Appliquons cette formule à la surface où la tension est fs et multiplions d'autre part haut et bas par $a = \sqrt{k/M}$:

$$F(t) - fs = \frac{a\,\Delta s}{k} \tag{21}$$

d'où l'on déduit finalement :

$$k = \frac{a\,\Delta s}{E} \cdot \frac{E}{F(t) - fa} \cdot \frac{F(t) - fa}{F(t) - fs} \tag{22}$$

fa étant la tension de la vapeur dans l'air ambiant.

Les valeurs numériques trouvées expérimentalement ($a = 3{,}65$, $\Delta s/E = 0{,}22$ en atmosphère calme et $\dfrac{E}{F(t) - fa} = 0{,}15$ dans les mêmes conditions) donnent enfin : $k = 0{,}11 \dfrac{F(t) - fa}{F(t) - fs}$: k très supérieur à 0,11.

Or ce coefficient de diffusivité k figure dans la formule :

$$\frac{dQ}{dt} = k\,\frac{df}{dz} \tag{12}$$

Si, comme le veulent les unités choisies dans les calculs précédents, on exprime dQ/dt en mm/jour, f en mm de mercure, z en cm, ce coefficient a la valeur, en air calme, de 0,21 : k (air) = 0,21.

D'autre part la formule approximative k (sol) = k (air) $\mu/\sqrt{2}$ où μ désigne la porosité, indique pour le sol étudié à la densité 1,5 et aux humidités considérées, une valeur de k (sol) de l'ordre de 0,01 à 0,04, très inférieure par conséquent à la valeur trouvée selon la dernière hypothèse. Celle-ci reviendrait donc à admettre que la diffusion de la vapeur dans le sol n'est pas une simple diffusion moléculaire mais correspond également à un mouvement de convection de la vapeur vers la surface. Le débit E — B n'est donc vraisemblablement qu'un débit vapeur apparent.

3/ l'hypothèse d'un débit liquide secondaire lié à la diffusion vapeur.

Le calcul avait conduit à la relation théorique suivante entre le débit dQ/dt et le gradient d'humidité dH/dz :

$$\frac{dQ}{dt} = \frac{a^2\sigma\,Ys}{10\int Ys\,dt} \cdot \frac{dH}{dz} \times B \tag{20}$$

avec (20') $$B = \delta - a2Ys\,\frac{\int \frac{d^2\delta}{dz^2}\,dt}{\int Ys\,dt}$$

Y représentant le taux d'évaporation dans le sol et Ys sa valeur limite en surface.

Cette relation rendait compte du fait expérimental à condition toutefois que le terme B explicité en (20') puisse être assimilé à une constante.

Pour qu'il en soit ainsi nous avons donc supposé en première hypothèse que le débit liquide δ était constant et égal à δo dans les couches superficielles; dès lors B n'était autre que δo.

Cette hypothèse ne correspondait en réalité qu'à une solution particulière de (20'). La solution la plus générale de cette équation consiste à poser que le débit liquide est la somme d'un terme constant δ_0 et d'un deuxième terme, proportionnel en tous points au débit vapeur : $K\Delta$

$$\delta = \delta_0 + K\Delta = \delta_0 + K\,aYs\,\exp\,(-z/a) \qquad (23)$$

En effet, si, calculant $d^2\delta/dz^2$, on porte la valeur trouvée dans l'équation (20'), on obtient :

$$B = \delta_0 + K\,aYs\,\exp\,(-z/a) - a^2Ys\,\frac{\frac{K}{a}\,\exp\,(-z/a)\quad Ysdt}{\int Ystd} \qquad (24)$$

soit après simplification :

$$B = \delta_0 \text{ (constante)}$$

ce qui est bien conforme à la condition recherchée.

Selon cette nouvelle hypothèse, d'un débit liquide secondaire proportionnel au débit vapeur Δ, le débit vapeur en surface Δs serait :

$$\Delta s = \frac{E - B}{1 + K} \qquad (25)$$

et non plus E — B comme il avait été trouvé précédemment. Cette diffusion vapeur, plus faible, n'implique donc plus un mouvement turbulent de la vapeur dans le sol. Il reste par contre à expliquer l'origine de ce débit liquide proportionnel au débit vapeur. Nous reviendrons plus tard sur ce phénomène dont nous poursuivons l'étude.

Conclusion

S'il est encore difficile d'expliquer parfaitement l'ensemble des résultats sur le desséchement du sol au-dessous du plan d'évaporation, il apparaît cependant que l'évaporation E est compensée par deux flux en surface que l'on peut chiffrer expérimentalement : d'une part un flux B assuré par le déplacement continu d'un film liquide provenant des profondeurs assez grandes s'évaporant en surface; d'autre part un complément que nous nommerons débit vapeur apparent : (Δ) app $= E - B$.

Que ce dernier corresponde en totalité ou en partie seulement à une diffusion vapeur, il se comporte qualitativement comme tel et ne contribue qu'au desséchement des strates peu profondes. C'est ainsi que cette composante (Δ) app. ne représenterait-elle même qu'une faible part de E, est le facteur essentiel du desséchement superficiel du sol. On a vu par exemple qu'un flux (Δ) app. égal seulement à 22 % de l'évaporation contribuait dans la proportion de 80 % au desséchement de la première tranche de 6 mm. Or en opérant sur une terre moins tassée ou en imposant une évaporation supérieure on aurait accru la part relative de (Δ) app. et précipité ainsi le desséchement de la surface.

On conçoit ainsi le rôle de cette diffusion vapeur apparente sur la formation du mulch naturel, couche de terre sèche, en équilibre d'hygroscopicité avec l'air, qui freine l'évaporation et joue ainsi un rôle considérable dans l'économie de l'eau.

Des expériences relatées plus haut ont montré que ce mulch apparaissait après une perte en eau de 40 mm environ; mais en rompant la cohésion du sol ou en augmentant l'évaporation on aurait augmenté le rapport (Δ) app./E et le mulch serait apparu après des pertes en eau de 4 à 5 mm seulement.

On soulignera pour finir l'intérêt que peut offrir la méthode d'investigation décrite ici pour étudier le rôle de la structure du sol et des façons culturales sur l'économie de l'eau, pour chiffrer les quantités d'eau susceptibles d'être acheminées du sous-sol jusqu'à la plante, pour préciser en outre l'humidité critique au-dessous de laquelle la diffusion liquide est impossible, différents problèmes dont il n'a pas été fait mention dans cet exposé mais dont nous avons abordé l'étude.

PLANTS AS DEW COLLECTORS

D. PHIL. INGA ARVIDSSON

SUMMARY

In order to compare different plant species as dew collectors investigations were carried out during the summers of 1954 and 1955 on Oland in the south east of Sweden and at Burg el Arab, 60 km west of Alexandria, Egypt. The dew was expressed in relation to the leaf area, in mm-s, and in per cent of the saturation weight. The mm values were compared to figures recorded simultanously by Duvdevani dew gauges and a Kessler-Fuess dew scale. Mainly the Duvdevani values were used as standard.

The average maximum values of condensed dew were for the best dew collectors amongst the species investigated 0.10 mm corresponding to 1/3 of the saturation weight. The maximum values for separate leaves were 0.20 mm corresponding to 2/3 of the saturation weight.

The plant species condensed the maximum of dew water at rather low Duvdevani values 0,075, 0,11 and 0,15 mm. There was a variation between the species.

For one and the same species there could be a small variation between nights having the same Duvdevani values. The Kessler-Fuess values varied in the same way as the plant values. The reason certainly was that the plant leaves and the Kessler-Fuess condensation surface were more sensitive to short periods of evaporation than the Duvdevani dew gauge.

Dew investigations were made during the summers of 1954 and 1955 at Olands-Smedby on the island of Oland, south east of the Swedish coast, and during the winter of 1956 at Burg el Arab in Egypt, 60 km west of Alexandria, in order to determine the maximum amount of dew that can be condensed upon plants and the dew values, related to a standard dew-gauge, at which this condensation is greatest. Different plant species were compared in these respects. The dew was expressed in relation to the leaf area in mm of the species of which it was possible to determine the leaf area, and in per cent of the saturation weight. Mainly Duvdevani dew gauges were used as a standard, but a Kessler-Fuess scale, made at the Swedish Meteorological and Hydrological Institute, was also used. The investigations made at Burg el Arab were part of investigations paid by a grant from UNESCO.

In 1954, *Plantago lanceolata*, *Chenopodium album*, *Fragaria viridis*, *Filipendula hexapetala* and *Solanum tuberosum* were investigated, the first three ones being the main material. Experiments were made at the Duvdevani-values 8 (0,35mm), 7 (0.27 mm), and 6 (0.20 mm). This year the dew was expressed in relation to the leaf area only.

Upon each of the species there condensed an equal amount of dew at Duvdevani 8, 7, and 6. The condensation upon *Chenopodium album* was almost twice as great as that upon *Plantago lanceolata* and *Fragaria viridis* or on an average: 0.100, 0.051, and 0.056 mm respectively.

Thus, the maximum amount of dew was constant for the different species and condensed at Duvdevani 6 or at a lower value.

In 1955, *Amaranthus sp.*, *Betula vulgaris* (sugar-beet), *Centaurea scabiosa*, and *Cichorium intybus* were included into the investigations. *Solanum tuberosum*, *Chenopodium album*, and the *Amaranthus* sp. formed one group, the two last-mentioned species being weeds in a potato-field. The experiments were carried out during two periods, one in July and one in August. *Plantago lanceolata*, *Fragaria viridis*, and *Filipendula hexapetala were* investigated in July only as, after a period of drought,

it was not possible to get material in August. The *Amaranthus sp.*, *Beta vulgaris*, and *Centaurea scabiosa* were investigated in August only.

The experiments were made at the Cuvdevani-values 7 (0.27 mm), 5 (0.15 mm), 4 (0.11 mm), and 3 (0.075 mm). For obtaining the weight of the leaves when saturated with water they were placed for twelve hours, the stalks in water, in saturated atmosphere. The leaf area was determined when the leaf was saturated with water, and the mm-values are, therefore, somewhat too low as the dew was condensed on the leaf when this had a saturation deficit and its area was smaller. Especially in August, the saturation deficits of the leaves were very great.

In relation to the leaf area, more dew was condensed upon *Chenopodium album* than on any other plant investigated. This can be seen from Table I. The max. average value in mm for *Chenopodium album*, 0.121, was about three times that for *Filipendula hexapetala* (0.041). Some species can thus condense three times as much as others per unit of area. When the dew was expressed in p.c. of the weight of the leaves when saturated, the relation between the species was different. Thus, the difference between *Chenopodium album* and *Solanum tuberosum* was then but small, *Chenopodium album* having thick leaves and *Solanum tuberosum* thin ones.

TABLE I

Dew in mm

	Max. average value (av. 50 leaves)	Maximum value (one sing. leaf)	*Dew in p.c. of the saturation weight* Max. average value (av. 50 leaves)	Maximum value (one sing. leaf)
Chenopodium album	0.121 ± 0.009	0.195	39.6 ± 3.0	67.2
Solanum tuberosum	0.085 ± 0.005	0.130	35.6 ± 2.3	66.2
Amaranthus sp.	0.083 ± 0.005	0.114	32.3 ± 2.3	53.8
Betula vulgaris	0.089 ± 0.005	0.113	22.3 ± 1.7	34.0
Centaurea scabiosa	0.075 ± 0.007	0.114	23.9 ± 2.4	43.4
Cichorium intybus	0.057 ± 0.005	0.135	25.9 ± 1.9	63.3
Fragaria viridis	0.052 ± 0.004	0.085	32.3 ± 2.6	55.6
Plantago lanceolata	0.044 ± 0.004	0.071	17.3 ± 0.8	26.1
Filipendula hexapetala	0.041 ± 0.001	0.076	24.5 ± 1.6	39.6

Betula vulgaris came next to *Chenopodium album* as regards the capacity of condensing dew, expressed in mm, but only *Plantago lanceolata* had a lower dew value than *Betula vulgaris* in p.c. of the weight of the leaf among the plants investigated. From the point of utilization of dew water, the values indicating the dew in p.c. of the weight of the leaf must be the most important ones. Thus, in this material, *Plantago lanceolata* must be pointed out as a particularly bad dew collector.

Solanum tuberosum, the *Amaranthus* sp., and *Betula vulgaris* condensed the same amount of dew whether the Duvdevani gauge recorded 4 or 7, or the maximum of dew was condensed at Duvdevani 4. *Cichorium intybus*, *Plantago lanceolata* and *Fragaria viridis* seemed to be able to condense as much dew even at Duvdevani 3, as at Duvdevani 7. As for the other species investigated, it was not possible to see from this material at which value they condensed the maximum amount of dew.

It only seemed as if *Chenopodium album* could condense more dew at Duvdevani 7 than at Duvdevani 4. Thus, most of the plant species investigated condensed the maximum amount of dew at Duvdevani 4 (0.11 mm) or 3 (0.075 mm).

In 1956, mainly annual herbs and some cultivated trees and bushes were investigated at Burg el Arab. The experiments were made at Duvdevani 2 to 7.

TABLE II

Dew in mm

	Max average value	Max. value (one single leaf or branch)	*Dew in p.c. of the saturation weight* Max. average value	Max. value (one single leaf or branch)
Hordeum vulgare	0.070±0.002	0.114	30.3±1.5	63.7
Hordeum murinum	0.049±0.007	0.093	45.0±5.1	63.3
Chenopodium murale	0.082±0.004	0.176	22.5±3.3	62.0
Enarthrocarpus strangulatus	0.083±0.009	0.155	29.9±1.8	55.7
Beta vulgaris var. pilosa	0.078±0.006	0.183	17.2±1.2	33.1
Achillea santolina			15.5±0.8	28.7
Tamarix articulata			9.6±0.5	26.4
Pittosporum viridiflorum	0.062±0.003	0.136	14.6±2.4	34.2
Myoporum laetum	0.022±0.002	0.046	4.9±1.0	13.5

(The names of the above species were given by Vivi Tackholm, Professor of Systematic Botany, Cairo University).

The Egyptian herbs condensed about the same amount of dew as the Swedish ones (table I and II). *Hordeum murinum* (wild barley), having the average value of 45.0% of the saturation weight, was undoubtedly the best dew collector in the Egyptian as well as in the Swedish material. The mm—values, however, were low—0.049 mm. *Chenopodium murale*, having comparatively thick leaves, had the highest mm-values but low values when measured in p.c. of the saturation weight. *Chenopodium album* in the Swedish material and *Chenopodium murale* in the Egyptian one, were very much alike, only *Chenopodium album* condensed so much more dew that its capacity of condensation was greatest in the Swedish material even when measured in p.c. of the leaf weight. *Beta vulgaris* var. *pilosa*, like the sugar-beet had a comparatively high mm-value and a low value in relation to the weight of the leaf.

A Tamarix tree always gave a considerable amount of precipitation around the tree during a dew night. Only a comparatively small part of the dew remained on the branches. To get an idea of the amount of dew condensed on the tree one would have to collect the precipitation from isolated branches. *Casuarina stricta*, when investigated, did not collect any dew. The bushes *Pittosporum viridiflorum* and *Myoporum laetum*, planted close to each other, were apparently very different as

dew collectors, the amount of dew condensed upon *Pittosporum viridiflorum* being three times that simultaneously condensed on *Myoporum laetum. Hordeum vulgare* condensed the maximum amount of dew at Duvdevani 5, *Chenopodium murale* at Duvdevani 4-5, *Hordeum murinum at* Dudvevani 3-4, *Beta vulgaris* var. *pilosa* and, *Enarthrocarpus strangulatus* at Duvdevani 3. The maximum condensation did not always take place at these values as, during periods of evaporation, the influence upon a Duvdevani gauge was smaller than that on thin leaves.

Concluding remarks:

Among the species investigated two groups could be distinguished. First the representatives of *Chenopodiaceae*, namely *Chenopodium album*, *Chenopodium murale*, *Beta vulgaris* var. *pilosa*, and the common sugar-beet. Being halophytes they condensed very much dew; the value expressed in mm was greater than that of the other species investigated. But because of their having thick leaves, the amount of dew when measured in p.c. of the leaf weight was not so great as that of a second group of thin-leaved representatives, for example the potato plant and wild and cultivated barley.From the point of the utilization of dew by the plants, this second group may be the most interesting one. But the first group is remarkable as regards its capacity of condensing and keeping water per unit of area.

The maximum average value for the best dew-collecting species was about 0.10 mm and 1/3 of the saturation weight. The maximum value for separate leaves was 0.20 mm and 2/3 of the leaf weight respectively.

Most of the species condensed considerable amounts of dew at Duvdevani 3. It must, therefore, be of interest to know the number of nights having dew corresponding to Duvdevani 3 or more. At Olands-Smedby, the dew was recorded in 1953, 1954, and 1955. From the middle of June to the middle of October there seem to have been about 60 dew nights. Condensation on plants must thus have been possible during half the number of nights. Unfortunately, there were no dew-recordings made from May to the middle of June. The farmers, however, state that there is hardly any dew during that part of the year. Oland is known as an area that is rich in dew. Hence, the dew-values from Oland are not representative of the whole of Sweden.

At Burg el Arab in Egypt, situated near the meditarranean coast and west of Alexandria, continuous dew recordings are being made since December 1956. The results of the recordings up to February 25th 1957, were kindly sent to Sweden by Dr. Fathi Taha, Director General of the Meteorological Institute, Kobri el Kobba, Cairo. Furthermore, recordings were made from December 1953 to June 1954. According to these recordings, condensation upon plants is possible during about 130 nights or one third of the nights of a whole year. There are two minima during a year. In 1954 the first minimum occurred during April and the first week of May. In 1956 it occurred principally during the first part of April when there was no dew at all in the nights. In 1956, the second minimum was recorded from the middle of August to October. However, it is not always possible to judge from a Duvdevani value whether there will be much dew condensed upon the vegetation. One night on Oland, when a Duvdevani value of 5 was recorded, the condensation upon all species investigated was but small. The reason was that a period of evaporation had occurred during the night. This could be seen from the Kessler-Fuess dew scale, which had reacted in about the same way as the plants.

VERGLEICHENDE MESSUNGEN DES NEBELNIEDERSCHLAGS

DR. J. GRUNOW
Meteorologisches Observatorium Hohenpeissenberg des Deutschen Wetterdienstes.

SUMMARY
Comparable Measurements of Fog Precipitation.

Results of some years comparable measurements of fog precipitation with the Hohenpeissenberg fog catcher are discussed. In addition to cloud physical conditions the exposition and height of locality is decisive for the amount of deposits from cloud air. The highest amounts are given in case of including warm air masses of maritim origin in drift. The droplet spectrum then indicates a range of 4 to 20 μ and a maximal diameter of 8 - 12 μ. The deposits are still more intensive with amounts of 2 - 3 mm/h in case of stemming cloudiness when rain is not actual. The air masses are then often degenerated by continental influence and the droplet spectrum indicates a wide range from 5 to 60 μ with a maximum of 12 - 18 μ. On the tops of the German upland mountains there is found a surplus of 1 - 2 times of precipitation amount in a year. It is compared with the amount of water deposited by fog precipitation on the Velebit (Jugoslavia), on Table Mountain (South Africa) and on Hokkaido (Japan).

1. VORBEMERKUNG.

Beobachtungen über zusätzliche Wasserablagerungen aus Nebelluft (fog drip) in einem Waldbestand des Hohenpeissenberges in 975 m Seehöhe regten im Jahre 1951 zur näheren Untersuchung einer Zusatzkomponente des Niederschlags an, dessen Studium die Meteorologische Weltorganisation in ihren Washingtoner Beschlüssen 1948 (Res. 139) empfohlen hat. Die Bedeutung dieser zusätzlichen Wasserspende für die Vegetation ist aus den Tropengebieten bekannt, wo in den Gebirgen oberhalb des Regenwaldes sich im Wolken- und Nebelgürtel der Kondensationszone als typische Vegetationsform der immergrüne « Nebelwald » entwickelt. Auch aus den aussertropischen Gebieten ist die Wirkung des Nebelniederschlags auf den Pflanzenwuchs belegt (1). Überall, wo Erhebungen zeitweilig in den Wolkenraum der Grundschicht hineinragen, wo heftige Talwinde an den Berghängen ausgesprochene Nebelgürtel in das Gebirge vosrchieben, wo feuchtwarme Luftströmungen vom Meer auf das Festland übertreten und Steigungsnebel hervorrufen, ist mit erheblichen Ablagerungen zusätzlicher Wassermengen aus Nebelluft zu rechnen.

Über die Grössenordnung des Nebelniederschlags waren bis dahin nur Hinweise aus älteren Arbeiten zu entnehmen (MARLOTH, LINKE, HARTMANN, DESCOMBES, DIECKMANN, RUBNER, Literatur bei (2)). Die Ergebnisse dieser verschiedenen Untersuchungen sind nicht miteinander vergleichbar, weil die abgelagerte Menge mit Art und Aufbau des ablagernden Vegetationsbestandes wechselt. Erst mit der Einführung eines definierten Nebelfängers, der an allen Orten eine gleichartige Ablagerungsfläche darbietet, wurde erstmals das Angebot der Atmosphäre an Nebelniederschlag einer vergleichenden klimatologischen Bearbeitung zugänglich gemacht. Hier wird über die Ergebnisse der bisher vorliegenden bzw. bekanntgewordenen Beobachtungsreihen berichtet.

2. ZUR MESSMETHODE.

Über die zur Messung des Nebelniederschlags angewandte Methode und deren

theoretische Begründung wurde auf der Konferenz in Rom 1954 berichtet ([3]). Einige Erfahrungen auf Grund sechsjähriger Messreihen sowie bekannt gewordene methodische Einwände seien hier besprochen.

a. *Die Linearität des Ablagerungsverhältnisses.*

Der Hohenpeissenberger Nebelfänger besteht aus einem Zylinder von Drahtgaze, die ein System von Ablagerungszylindern kleinsten Durchmessers (0.25 mm) bildet. Die grundlegende Voraussetzung des Messverfahrens, das lineare Verhältnis zwischen Windgeschwindigkeit und Ablagerungsmenge, ist erfüllt ([4]).

b. *Die Niederschlagszurückhaltung am Netzgitter.*

Am Netz des Nebelfängers findet, ähnlich wie am Vegetationsbestand, eine Zurückhaltung (interception) von abgelagertem Niederschlag statt, die im Durchschnitt mit 10 % anzusetzen ist. Dieser Fehlbetrag fällt grösstenteils der Verdunstung anheim oder gerät durch Abwehen abgelagerter Tröpfchen in Verlust. Gegenüber der früher ([3]) beschriebenen und abgebildeten Form wurde neuerdings der untere Rand des Zylinders an den drei Stützen heruntergezogen und der Ablauf der nach unten zusammenlaufenden Tropfen um 5 — 10 % verbessert, so dass die Niederschlagszurückhaltung am Drahtgitter heute nur noch 1 — 2 % beträgt. Ganz ausschalten lässt sich dieser Verlustposten nicht. Die effektiv am Gitter abgelagerte Wassermenge liegt darum etwas höher als die Messung anzeigt.

c. *Die effektiv wirksame Ablagerungcsfläche.*

In einer Untersuchung über den Nebelniederschlag am Tafelberg bei Kapstadt, bei der Hohenpeissenberger Nebelfänger zum Einsatz kamen, leitete NAGEL ([5]) den Wirkungsgrad der effektiven Ablagerungsfläche aus der teilweisen gegenseitigen Abdeckung der einzelnen Drähte am Rande des projizierten Zylindermantels zu 0.56 und nach Bedeckung des Netzes mit abgelagerten Tropfen zu 0.75 der Auffangfläche des Niederschlagsmessers ab. Nach voller Benetzung dürften weniger als 10 % der gegen den Zylinder anströmenden Wolkentröpfchen den Zylinder durchströmen, ohne am Ablagerungsvorgang beteiligt zu werden. Die am Nebelfänger aufgefangenen Mengen werden aber mit dem Messglas des Niederschlagsmessers ausgemessen und damit auf dessen Auffangfläche 200 cm^2 bezogen. Die auf die Einheitsfläche stattgefundene Ablagerung liegt also höher als dem Messergebnis zu entnehmen ist.

d. *Der Einfluss seitlich auffallenden Niederschlags.*

Die zusätzliche Menge des Nebelniederschlags wird aus dem Messersgebnis zweier Niederschlagsmesser, von denen der eine mit einem Nebelfänger ausgerüstet ist, zu $N = (R + N) - R$, der Differenz der mit beiden Messern aufgefangenen Mengen, abgeleitet. Die Voraussetzung, dass der Mehrbetrag des mit Nebelfänger ausgerüsteten Niederschlagsmessers ausschliesslich durch die horizontal antreibenden Nebeltröpfchen zustande kommt, ist im Einzelfall nicht gültig. Wenn bei stärkerem Wind zugleich auch Regen fällt und der Einfallswinkel der Regentropfen 8^0 übersteigt, vergrössert das Netzgitter die Auffangfläche des Niederschlagsmessers. Andererseits werden dann am Netz aufgefangene oder zusammengelaufene Tropfen in stärkerem Masse abgeweht, ohne in das Sammelgefäss abzulaufen. Eine geringe Menge seitlich aufgefangenen Regenwassers wird, solange die Luft nicht voll gesättigt ist, d.h. kein Nebel herrscht, vom Netz wieder verdunsten. Diese die Wassereinnahme

erhöhenden und vermindernden Effekte gleichen sich im Mittel annähernd aus, wie Vergleiche im Auffang beider Geräte — mit und ohne Nebelfänger — bei nebelfreiem Wetter bestätigen (3). Es besteht kein Grund zu der Annahme, dass der Mehrbetrag des Nebelfängers bei Regenfall, wenn gleichzeitig auch Nebel herrscht, nicht durch die abgelagerten Nebeltröpfchen verursacht, sondern durch seitlich am Netz aufgeschlagene Regentropfen wesentlich verfälscht sei.

Bei Schneefall spielt dieser Effekt eine nur untergeordnete Rolle. Die leichten, schon bei mässigen Wind mehr horizontal auffallenden Schneeteilchen verstopfen schnell das Netz, das sich danach immer mehr wie ein geschlossener Zylinder von 100 mm ø verhält. In diesem Zustand werden die in der Strömung mitgeführten Niederschlagsteilchen zum grössten Teil um den Zylinder herumgeführt und nicht mehr auf dessen Oberfläche abgelagert (9, 4).

Um den Einfluss seitlich auffallenden Niederschlags auszuschalten, wandte Nagel (5) bei seinen Auswertungen das folgende Verfahren an: Als Grenzwert zur Unterscheidung von Nebelniederschlag und Nieselregen (drizzle) wird eine Intensität von 0.1 mm/h angenommen. Zeitabschnitte, in denen im Regenschreiber (R) mindestens diese Menge registriert wurde, werden bei der Aufzeichnung des zweiten Regenschreibers mit Nebelfänger (RN) nicht berücksichtigt. Als Nebelniederschlag werden also praktisch nur diejenigen im Gerät RN aufgezeichneten Mengen gewertet, bei denen das Gerät R eine gerade Linie aufzeichnete. Er erhält so eine Intensität des Nebelniederschlags im Mittel des Beobachtungsjahres von 3.75 mm/h (gegenüber einer mittleren Intensität des Regenfalls von 1.84 mm/h). Rechnungen von Schumann (6) machen aber für den Gehalt an flüssigem Wasser, den die Hinderniswolke über dem Tafelberg, das « Tafeltuch », durch eine Fläche von 1 m^2 passieren lässt, bei einer beobachteten mittleren Windgeschwindigkeit von 13 m/sec eine Menge von 46.8 mm/h wahrscheinlich, also einen gegenüber dem experimentellen Befund mehr als 12 mal höherem Betrag. Zur Erklärung dieser Diskrepanz zieht Nagel verschiedene Gründe zumeist wolkenphysikalischer Art und lokale Einflüsse am Messfeld (z. B. reduzierte Windgeschwindigkeit in Höhe des Nebelfängers) heran, messmethodisch könnte nur eine Minderleistung des Nebelfängers (zu kleine effektive Ablagerungsfläche des Netzgitters, strömungstechnische Benachteiligung des Standortes) diese Differenz begründen.

e. *Horizontale Ablagerung von Niederschlag durch die Vegetation.*

Ein nennenswerter Auffang von Regentropfen bei stärkerem Wind seitlich am Netzgitter findet nur statt, wenn die Regentropfen sehr klein (z.B. bei Sprühregen 0.1 — 0.2 mm ø oder bei leichtem Regen bis 0.5 mm ø) und deren Einfallswinkel entsprechend gross ist. Ein grösserer Teil dieser Tropfen wird, ebenso wie vom Nebelfänger, auch von einem höheren Vegetationsbestand seitlich abgelagert, von einem gewöhnlichen oder hangparallelen Niederschlagsmesser aber nicht erfasst und, wenn keine Hindernisse vorhanden sind, mit der Strömung weit davongetragen, sofern sie, z.B. nach Überwehen eines Rückens, überhaupt zur Erde ausfallen und nicht vorher unter der Leewirkung verdunsten. Der Nebelfänger übt in diesem Fall dieselbe Wirkung aus wie ein höherer, gestaffelter Waldbestand, für dessen Standort die Messung gültig sein soll.

f. *Einfluss der Ablagerungshöhe.*

Die stärksten Ablagerungen an einem Vegetationsbestand finden in Höhe des Kronenraumes, in einer Zone stärkeren Windes statt, als in Bodennähe, in Höhe des ablagernden Nebelfängers, gegeben ist. Die durch die natürliche Vegetation abgelagerte, dem Waldboden zufallende und in den Wasserkreislauf einbezogene

TABELLE 1

Ergebnisse vergleichbarer Messungen des Nebelniederschlags mit Nebelfänger. Nebelzuschlag, ausgedrückt in prozentualer Abweichung vom Niederschlag.

$$\frac{(RN - R)}{R} \cdot 100\ (\%).$$

Monatsmittel des Beob. Zeitraums.

Station	1 Bremer-haven	2 Darm-stadt	3 Hümmel	4 Ob. Hor-lofftal	5 Neuhof	6 Kl. Feldberg	7 Wasser-kuppe
Geograph. Lage	Nordsee-küste	Odenwald	Eifel	Vogelsberg	Hunsrück	Taunus	Rhön
Seehöhe (m)	6	263	460	520	600	807	921
Beob.Zeit	VI.52 –V.55	I.–V.53	VIII.54 –XII.54 V.–X.55	I.53 –I.55	VIII.54 –XII.56	IV.54 –III.57	XI.52 –III.57
Jan.	26	3		72	63	180	282
Febr.	**40**	13		74	55	91	170
März	18	–19		29	49	115	208
April	3	–16		22	27	80	135
Mai	5	–17	*–13*	*10*	10	45	83
Juni	–8		7	18	21	*43*	*72*
Juli	7		–10	17	*7*	53	81
Aug.	–8		–8	20	15	76	87
Sept.	*–10*		–6	26	18	87	152
Okt.	–7		–5	41	18	113	223
Nov.	4		–3	**81**	44	174	326
Dez..	30		12	59	**66**	**204**	**351**
Jahr	6			35	32	102	166
R(mm)	797			884	1068	1068	1198
RN(mm)	835			1197	1414	2155	3180
Sommer	–2			17	16	64	100
(IV-IX) R(mm)	485			506	550	576	709
RN(mm)	474			593	637	941	1421
Winter	16			59	50	145	260
(X-III) R(mm)	312			379	517	491	489
RN(mm)	361			604	777	1214	1759
Wi : So				3.5	3.1	2.3	2.6
Max.Zuschlag	48	13	12	124	87	315	924
R(mm)	43	29	100	14	19	68	14
RN(mm)	63	33	111	32	36	284	145
Monat	XII.52	II.53	XII.54	XI.53	II.56	XII.56	XI.52

8 Stötten	9 Gr.Falken- stein	10 Hohenpeis- senberg	11 Nebelhorn	12 Sljeme	13 Zavizan	14 Tafelberg
Schwäb. Alb	Bayer. Wald	N-Alpen- vorland	Allgäuer Alpen	SE-Alpen- vorland Jugoslavien	Velebit Adriat.Küste Jugoslavien	Kapstadt Südafrik. Union
734	1313	960	1932	999	1620	1067
XI.52 –III.57	VI.–X.54,55 XII.55 –III.57	XI.51 –III.57	VI.–IX. 52 – 54	X.54 –VI.56	IX.54 –VI.56	IV.54 –III.55
67	85	70		**45**	**416**	**1141**
47	62	80		4	161	*214*
45	124	47		21	107	576
58	48	55		12	198	286
17	70	32	(92)	8	119	254
15	47	21	91	–1	103	280
25	*33*	23	*81*	*–7*	*79*	280
9	38	*12*	126	–3	110	435
27	60	33	180	1	112	333
52	112	56	(294)	41	125	340
81	89	93		29	228	430
115	**192**	**94**		20	412	372
41	75	39		12	181	320
1104	1211	1113		1412	2006	1931
1558	2118	1548		1576	5644	8126
						(Winter)
24	44	27		1	117	297
681	656	799		828	857	1376
842	947	1012		834	1863	5463
						(Sommer)
69	111	71		27	230	379
423	555	314		584	1149	556
716	1171	535		742	3781	2662
2.9	2.5	2.6			2.0	1.3
372	208	220	397	86	623	1141
44	82	24	64	42	150	38
208	253	78	318	78	1085	469
XII.56	XII.56	XI.53	1.–13.X.54	I.55	XII.55	I.55

Wassermenge aus Ablagerungen ist also viel grösser, als am Nebelfänger aufgefangen wurde. OURA (7) hat mit Netzgittern in Höhe der Baumkronen (15 — 17 m) etwa 6 bis 10 mal so viel an Ablagerungen aus Nebelluft gemessen als in Bodennähe des Freilandes. Bei Messungen auf dem Hohenpeissenberg (8) wurde am Rande eines 60- bis 75- jährigen Fichtenbestandes für die auf den Waldbodeng elangte Wassermenge ein Faktor von 3.17 ermittelt, um die mit Nebelfänger in 1.5 m Höhe ermittelten Zusatzmengen darauf zu beziehen.

Aus allen vorstehend besprochenen Erwägungen heraus ergibt sich zwingend eine Folgerung : Die mit dem Nebelfänger aus der Differenz RN — R errechneten Beträge des Nebelniederschlags stellen Mindestwerte dar, die in der Natur wahrscheinlich überboten werden.

Die anschliessend besprochenen Messergebnisse beziehen sich ohne Einschränkung auf die Differenzbeträge RN — R bzw. deren prozentuale Mengen $\frac{(RN-R)}{R}.100\%$ (Tabelle 1). Die Werte sind monatsweise über die einzelnen Beobachtungsjahre gemittelt und daraus die Halbjahrs- und Jahreswerte abgeleitet. Da die Beobachtungszeiträume nicht genau übereinstimmen, sind die Werte nicht streng miteinander vergleichbar. Es zeigt sich jedoch, dass Jahresgang und Grössenordnung der Nebelsuschläge sich von Jahr zu Jahr recht ähneln und ein charakteristischer Jahresgang auch schon aus kurzen Beobachtungsreihen abgeleitet werden kann.

3. WIRKUNGEN DES NEBELNIEDERSCHLAGS.

Als spezielles Thema dieser Tagung der wissenschaftlichen Hydrologie ist die Frage nach dem Einfluss der Vegetation auf den Wasserkreislauf gestellt worden. Für die Ablagerung grösserer, hydrographisch ins Gewicht fallender Mengen von Nebelniederschlag spielt neben dem Nebel das Vorhandensein eines Vegetationsbestandes, der sich der anströmenden Nebelluft entgegenstellt, eine wichtige Voraussetzung. Im Flachland reicht der verhältnismässig geringe Nebelanfall gerade aus, den Waldniederschlag durch Herabsetzung der Niederschlagszurückhaltung infolge zusätzlicher Benetzung der Kronen etwas zu erhöhen. Von Bedeutung im Hinblick auf die Ablagerung zusätzlicher Wassermengen ist allein der Bergnebel im Gebirge, der Steigungsnebel im geneigten Gelände und der Küstennebel, sofern er gegen einen Vegetationsbestand anströmt.

a. *Wirkung des Bergnebels.*

Untersuchungen über den Niederschlag im Bergwald des Hohenpeissenberges (975 m) (8) zeigen, dass der durch die Niederschlagszurückhaltung (interception) in Verlust gehende Niederschlagsanteil, je nach Lage und Art des Bestandes bis zu 50 % des Jahresniederschlags, durch die aus Wolkenluft abgelagerten Nebeltropfen nicht nur ausgeglichen, sondern erheblich überkompensiert wird. Am Rande eines etwa 60 jährigen Fichtenbestandes wurde für die zum Waldboden gelangende Wassermenge als Nebelzuschlag zum Jahresniederschlag ein Anteil von 54 % ermittelt. Bei anhaltenden Nebelwetterlagen erreichte der am Waldboden aufgefangene Niederschlag das 2,5 fache der im Freiland gemessenen Menge. Im Bestandsinneren eines Westhanges wurde durch die Wirkung des Nebels noch 20 % mehr als im Freiland gemessen. Weitere Beispiele über Mehrerträge im Walde, die auf die Nebelwirkung zurückzuführen sind, wurden in dem der Konferenz in Rom vorgelegten Bericht gegeben (3).

b. *Wirkung des Steigungsnebels.*

Steigungsnebel treten überall auf, wo feuchte Luft durch die gegebenen orographischen Verhältnisse zum Aufsteigen gezwungen wird und kondensiert. Es liegen ausführliche Beschreibungen über die durch Steigungswinde vermehrte Feuchtigkeit an den Luvseiten der Afrika und Südamerika durchziehenden Gebirgsketten vor. Sie rufen an jeder Stufe, die von den feuchten Meeresluftströmungen überquert wird, breite Wolken- und Nebelzonen hervor. Die Ablagerungen sind dort besonders ergiebig, wo durch die Orographie die Stauwirkung dynamisch verstärkt und die mittlere Windgeschwindigkeit dadurch erhöht wird. So wird in Eritrea nahe bei Asmara über der Wasserscheide, wo kein hydrographisches Einzugsgebiet vorhanden ist, die Wasserablagerung aus Steigungsnebel zum Betrieb einer Talsperre benutzt ([10]), und die Nebeloase Erkowit im südnubischen Küstengebirge, eine Insel immergrüner hygrophiler Vegetation inmitten einer Wüstensteppe mit nur 150 mm Jahresniederschlag (winterlich rd. 67 mm), verdankt ihre Entstehung den vom Rotmeergraben zum abessinischen Hochland aufsteigenden winterlichen Nebeln ([11]). Für den Tafelberg hat Nagel ([12]), auf den Rechnungen von Schumann ([6]) and seinen eigenen, sehr kritischen Untersuchungen mit Nebelfänger aufbauend ([5]), die Nutzung des atmosphärischen Angebotes an Nebelniederschlag zur Bereitstellung zusätzlicher Wasserreserven überprüft und errechnet, dass ein Gitter von geeigneter Drahtgaze von 1.5 Im Höhe und 2 km Länge jährlich eine Wassermenge von 2 000 000 gal (1 gal (engl) = 4.54 Liter) zur Ablagerung bringen würde.

c. *Wirkung des Küstennebels.*

Hinweise über die Wirkung von Küstennebel, der zumeist durch die Mischung verschieden temperierter Luftmassen im Grenzbereich zwischen Land und Meer entsteht, oft aber auch durch einen Steigungseffekt des Seewindes an küstennahen Erhebungen verstärkt wird, sind von der irischen Westküste, den Azoren, den kanarischen Inseln, der Insel Ascension, von Java u.a. Orten bekannt. Durch Messungen von Isaac ([13]) belegt sind die Ablagerungen an den mit Wald bestandenen sanften Erhebungen des Cascade Head Experimental Forest nahe der Oregonküste. Die am Waldboden innerhalb des Bestandes aufgestellten Regenmesser fingen in 18 ausgewählten nebelreichen Wochen 44 % mehr Niederschlag als im Freiland auf, während in den nebelfreien Perioden infolge Zurückhaltung durch die Baumkronen 40 % weniger gemessen wurden.

In den grossangelegten Untersuchungen auf der Insel Hokkaido (Japan) über die nebelabfangende Wirkung von Waldbeständen an der Küste hat Oura ([7]) die Wirkung verschiedenartiger Bestandsformen verglichen. Die stärksten Ablagerungen wurden bei einem aufgelockerten Bestand einzeln stehender Nadelbäume ohne niedrige Zweige gefunden, der von der Nebelluft mehr durchströmt wird als ein dichter, bis zum Boden hin geschlossener Bestand. Die turbulente Strömung über dem Kronenraum bringt auch einen vertikalen Austausch mit Ablagerungen inmitten eines Bestandes von oben her mit sich, jedoch betrug die von der horizontalen Anströmung herrührende Ablagerung etwa dreimal so viel als die durch den Vertikalaustausch bewirkte.

4. Die Ablagerungsbedingungen.

Die Beziehung, nach der die Ablagerung von Masseteilchen in einer Potentialströmung an Hindernissen erfolgt, hat Albrecht ([9]) für Zylinder abgeleitet. Sie findet nicht nur zur Klärung der theoretischen Voraussetzungen der Wirkung eines

Nebelfängers Anwendung, sondern bildet auch die Grundlage zur Beurteilung der verschiedenen Ablagerungsmengen bei einem klimatologischen Vergleich. Ausser den Faktoren, die sich auf Form und Dimensionen der ablagernden Hindernisse beziehen und nur für streng geometrische Formen, nicht aber für die natürliche Vegetation abgeleitet werden können, wirken auf die Ablagerungsmenge der Gehalt der Luft an abzulagernden Wassertröpfchen, die Strömungsgeschwindigkeit und die Ablagerungszeit ein.

Diese drei Faktoren werden von den meteorologischen Bedingungen am Beobachtungsort gesteuert und durch die örtlichen Gegebenheiten variiert. Die meteorologischen Bedingungen hängen einmal von gewissen klimatologischen Voraussetzungen zur Nebelbereitschaft ab, die sowohl im Makroklima, im Mesoklima und im Lokalklima des Standortes gegeben sind. Die orographische Komponente des Lokalklimas wird in erster Linie durch den Hangeffekt ausgelöst, der, geometrisch gesehen, die Kondensation auf der Luvseite fördert, auf der Leeseite die Wolkenauflösung bedingt und durch die dynamische Wirkung des Strömungsfeldes lokale Verstärkungen oder Abschwächungen hervorruft. Die aktuellen Fälle von Nebelniederschlag werden dann durch die jeweilige Wetterlage ausgelöst.

Beide Komponenten, die klimatologischen Voraussetzungen und die Wetterlage, bestimmen das Kondensationsniveau, den Wassergehalt der ablagernden Wolken als eine Funktion der in die Strömung einbezogenen Luftmasse (Grösse und Menge der Wolkentröpfchen), die Luftbewegung, durch die Richtung und Geschwindigkeit der ablagernden Strömung gegeben ist, und die Andauer der Nebelwetterlage, durch die die Ablagerungszeit bestimmt wird.

5. Die Ablagerungsmengen.

Zur Erklärung der verschiedenen Mengen von Nebelniederschlag, wie sie in der Tabelle 1 von insgesamt 14 Stationen vorgelegt werden, gelten zunächst die gleichen Gesichtspunkte, wie sie von Serra ([14]) mit seinen « lois de la pluviosité » für die Deutung der Niederschlagsmengen herangezogen wurden und hier auf die Kondensation zu beziehen sind. Alle den Kondensationsvorgang auslösenden und steigernden Momente tragen auch zur Bildung und Steigerung des Niederschlags bei. Es sind dies

(1) die Seehöhe,
(2) der Kontinentalitätseffekt,
(3) der Hangeffekt.

Hinzu kommt (4) ein Temperatureffekt, sofern er (z.B. bei Mischung verschieden temperierter Luftmassen) Anlass zur Nebelbildung gibt. Keiner dieser Faktoren ist für sich allein massgebend. Sie überdecken sich in ihrer Wirkung, wie es in klimatogischer Sicht aus ihrem wechselseitigen Einfluss auf die Bewölkungs- und Niederschlagsverhältnisse ersichtlich wird, und sie unterliegen, wie diese, einem jährlichen Gang.

a. *Abhängigkeit von der Seehöhe.*

An der flachen Nordseeküste bei Bremerhaven (Nr. 1) treten Ablagerungen nur in den Wintermonaten mit ca. 30 % Zuschlag beim Auftreten von Mischungsnebel in Erscheinung. Eine kurze Messreihe von der Wetterwarte Darmstadt (Nr. 2) aus 263 m von dessen Messfeld auf einer windgeschützten Waldlichtung bestätigt, dass in dieser Höhe bei schwacher Ventilation noch keine nennenswerten Ablagerungen zustandekommen. Im Durchschnitt des Beobachtungszeitraums I. — V. 1953 werden mit Nebelfänger nur 90 % der Menge des normalen Niederschlagsmessers, bei

Berücksichtigung der Zurückhaltung am Netzgitter also praktisch gleichwertige Mengen gemessen.

Mit wachsender Seehöhe eines Beobachtungsortes verringert sich dessen Abstand vom Kondensationsniveau, bei ansteigendem Gelände gelangt er von einer gewissen, in den einzelnen Klimazonen wechselnden Höhe an immer häufiger in den Wolkenraum der Grundschicht. Die Steigerung des Nebelzuschlags mit der Seehöhe wird aus dem Vergleich einiger, von der Küste etwa gleichweit entfernter norddeutscher Stationen (Nr. 3 bis 7) ersichtlich. Hümmel liegt mit 460 m NN zumeist noch ausserhalb der Kondensationszone und die Ergebnisse des Nebelfängers zeigen das bekannte Defizit, das durch die Zurückhaltung am Netzgitter hervorgerufen wird. Erst bei der trüben Dezemberwitterung kommt ein geringer Überschuss zustande. Schon die Messungen im Horlofftal (Vogelsberg) in 520 m NN und beim Forstamt Neuhof (Hunsrück) in 600 m NN bringen einen Jahresüberschuss von mehr als 30 %, der sich in den Wintermonaten bis zum 0,5- bis 0,6-fachen erhöht. Auf dem Kl. Feldberg (Taunus) in 807 m NN steigert sich der Nebelzuschlag schon auf das Doppelte der Freilandmenge. Dieser Standort ist von den Messungen von Linke ([15]) her bekannt, wo innerhalb eines Bestandes am Waldboden mit einem gewöhnlichen Niederschlagsmesser im Durchschnitt von 6 Beobachtungsjahren rund 60 % mehr Niederschlag aufgefangen wurde als im Freiland. Berücksichtigt man noch die an nebelfreien Tagen festgestellte Niederschlagszurückhaltung von 30 %, so ergibt sich für diesen Standort nach Messungen am Waldboden ein Nebelzuschlag von gleicher Grössenordnung, wie er jetzt mit dem Nebelfänger ermittelt wurde. Mit den Messungen von der Wasserkuppe (Rhön) in 921 m NN, einem windexponierten Standort ohne ablagernden Waldbestand, steigert sich das Angebot an zusätzlichem Nebelniederschlag auf einen Jahreszuschlag vom 1,6-fachen, der im Winterhalbjahr bis zum 2,6-fachen anwächst und selbst in der Vegetationszeit noch die Bezugsmenge verdoppelt.

Überträgt man die Messergebnisse dieser Stationen in ein halblogarithmisches Diagramm (Abb. 1), so ergibt sich eine Zunahme des Nebelzuschlags mit der Seehöhe nach einer Exponentialfunktion, die selbst für die vom Tafelberg (Nr. 14) mit Nebelfänger ermittelten Zuschläge — trotz völlig andersartiger Voraussetzungen für die Nebelbildung an diesem Standort — Gültigkeit zu haben scheint. Diese Zunahme entspricht der Häufigkeit des Auftretens von Bergnebel, der bei diesen Stationen hauptsächlich bei Zufuhr maritimer Luft aus dem Westsektor eintritt. Fasst man die von Dreyling ([16]) für eine Reihe mitteleuropäischer Gipfel abgeleitete Nebelbereitschaft für die häufigsten Windrichtungen SW, W, NW zusammen, so ergibt sich ebenfalls ein Anstieg nach einer Exponentialfunktion. Damit wird ein ursächlicher Zusammenhang beider Erscheinungen bestätigt.

b. *Abhängigkeit von der Kontinentalität.*

Je weiter eine Luftmasse in das Innere eines Kontinents einfliesst, desto trockener wird sie. Die Nebelablagerungen müssen darum mit zunehmender Entfernung von der Küste geringer werden. Vergleicht man die Ergebnisse von Stötten (Nr. 8) und vom Hohenpeissenberg (Nr. 10) mit den Werten der ersten Stationsgruppe, so werden dort 40 % Nebelzuschlag in etwa 600 m Seehöhe gemessen. Die im Lee der norddeutschen Mittelgebirge wieder absinkenden, trockener gewordenen Luftmassen kommen nach Überqueren des Rhein-Main-Gebietes und deren Randgebirgen am Schwäbisch-Fränkischen Jura wieder zum Aufsteigen und lagern in Stötten in freier Lage auf der Hochfläche der Schwäbischen Alb den gleichen Betrag erst in 734 m ab. Der Anfall an Nebelniederschlag auf den nach Westen und Norden zu abfallenden Hängen der östlichen Alb mit einem winterlichen Zuschlag von 69 % wird an den dort häufig auftretenden schweren Rauhfrostbrüchen in Waldgebieten, Obstplantagen und an Freileitungen der Energieversorgung ersichtlich. Hinter dieser von SW nach

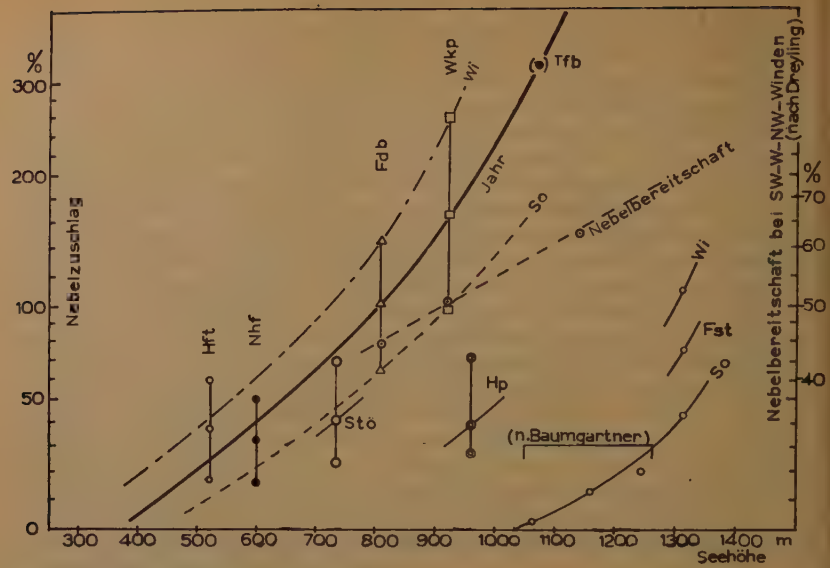


Abb. 1 — Abhängigkeit des Nebelzuschlags von Seehöhe und Kontinentalität.

NE streichenden Schwelle steigt südlich der Donau das Gelände erneut im Alpenvorland wieder an. Hier am Alpenrand sammelt der Nebelfänger den 0,4 fachen Zuschlag erst in 960 m Seehöhe.

Andere Verhältnisse bietet der Falkenstein (Nr. 9) in 1313 m, dessen Jahres-zuschlag von 75 %, verglichen mit dem des Hohenpeissenberges (960 m) von 39 % und auf dessen Seehöhe umgerechnet, noch relativ niedriger liegt. Aus Profilmessungen am Grossen Falkenstein hat Baumgartner ([17]) als Grenze, bis zu der Nebelniederschlag in Erscheinung tritt, die Höhenlage von 1050 m abgeleitet. Die Ergebnisse seiner Stationen 2 — 5 aus den weniger ergiebigen Sommermonaten (VI. — X.) in die Darstellung (Abb. 1) übertragen, ergibt eine Höhenabhängigkeit, die einer gleichen Exponentialfunktion folgt, wie die Werte der ersten Stationsgruppe, nur dass sie wegen der weiteren Entfernung vom Meer in einer grösseren Seehöhe verläuft. Wegen der Streichrichtung des Bayerischen Waldes von NW nach SE tritt ein Anstau nur bei Strömungen zwischen W und SW ein, einer Richtung, die auch am Hohenpeissenberg durch die Leitwirkung des Alpenmassivs die meisten Staulagen ergibt. Bei beiden Stationen ist aber auch eine erhöhte Nebelbereitschaft bei Ostströmung im Zusammenhang mit Störungen aus dem Mittelmeerraum gegeben. Obwohl diese Ostwetterlagen am häufiigsten im April auftreten, ergeben die Messungen von Baumgartner auf dem Südosthang, der bei den weiter nördlicher gelegenen Gebirgen als Leelage in Erscheinung tritt, auch im Sommer einen höheren Auffang mit dem Nebelfänger als auf dem Westhang.

c. *Die Verhältnisse am Alpenrand.*

Ein Vergleich von Hohenpeissenberg mit Ergebnissen einiger Sommermonate vom Nebelhorn (Allgäuer Alpen) (Nr. 11) aus 1932 m zeigt wiederum die Zunahme der Nebelniederschläge mit der Seehöhe unter sonst vergleichbaren klimatischen Verhältnissen. Die Zuschläge steigern sich zum Herbst bis zum 6-fachen der hier

gemessenen Mengen. Allerdings treten dort Steigungsnebel bei Ostlagen, die am Hohenpeissenberg sich als äusserst ergiebig erweisen, nicht mehr in Erscheinung, so dass die aufgefundene Höhenabhängigkeit zwischen diesen Stationen nicht mehr gültig ist. Aus höheren Lagen liegen leider keine Messungen vor, um die Höhe maximaler Ablagerungen ableiten zu können. Oberhalb des Wolkenraumes der Grundschicht und innerhalb des Alpengebietes dürften sie wieder abnehmen. Da die Regionen oberhalb der Baumgrenze aber nur noch bodennahe Hindernisse oder den Hang selbst zur Ablagerung darbieten, spielen diese räumlich sehr begrentzen Gebiete hinsichtlich des Nebelzuschlags forstwirtschaftlich oder wasserwirtschaftlich nur noch eine geringe Rolle.

d. *Messungen im Mittelmeerraum.*

Für das dem SE-Rand der Alpen vorgelagerte Slema-Gebirge (Nr. 12) erfolgt eine Stauwirkung im Zusammenhang mit Störungen aus dem Mittelmeerraum auf der Zugstrasse Vb. Ein Nebelzuschlag tritt hier nur noch in der Zeit von Oktober bis zum Mai in Erscheinung. Um so stärkere Ablagerungen werden aber an der Adriaküste bei der in 1620 m im Küstengebirge Velebit gelegenen Station Zavizan (Nr. 13) gemessen, wo der 1,8-fache Jahresbetrag des freien Niederschlags zusätzlich abgelagert wird.

e. *Messungen vom Tafelberg.*

Von den klassischen Messungen von Marloth her sind die hohen Ablagerungsmengen vom Tafelberg bei Kapstadt bekannt. Die Hinderniswolke um die höheren Regionen, das « Tafeltuch », erscheint — auch an schönen Sommertagen, sofern nur das Kondensationsniveau unterhalb der Gipfelhöhe 1092 m erreicht wird —, wenn die Luft vom Ozean aus SE an den schroff aufsteigenden Hängen adiabatisch aufsteigt. Eine einjährige Messreihe mit dem Hohenpeissenberger Nebelfänger nahe der Gipfelstation der Seilbahn in 1067 m (Nr. 14) brachte einen Nebelzuschlag von mehr als dem dreifachen des fallenden Niederschlags. Bei der von Nagel [5] angewandten strengeren Definition, die nur Ablagerungen ausserhalb der Dauer eines Regenfalls zählt, stehen sich immer noch den 1940 mm Regen zusätzlich 3294 mm Nebelniederschlag gegenüber. Auf dem luvseitigen, östlichen Plateau des Tafelberges, wo auch Marloth gemessen hat, dürften — nach den Feststellungen von Nagel — die Ablagerungen wesentlich, vielleicht um das zwei- bis vierfache, höher liegen als an der Kabelbahnstation.

6. Der Jahresgang der Ergiebigkeit des Nebelniederschlags.

Mit dem Jahresgang anderer meteorologischer Elemente, insbesondere dem Bewölkungsgrad, der Bedeckung mit unteren Wolken und der Wolkenhöhe, wie sie aus flugmeteorologischen Bearbeitungen bekannt ist, der Tage mit Nebel u.a. unterliegt die Menge des Nebelniederschlags einem jährlichen Gang, der noch, je nach Standort, durch den Jahresgang von Windrichtung und Windstärke im Hinblick auf die Wirkung der Hangeffekte variiert wird. Die ergiebigsten Ablagerungen treten — den Tafelberg mit seinen ganz anderen klimatischen Voraussetzungen ausgenommen — allgemein in den Wintermonaten auf. Auf den Bergstationen steht dem Maximum im Dezember der November und Januar wenig nach. Ein sekundäres Maximum zeigt sich noch, besonders bei den Stationen des SE-Raumes, im März und April im Zusammenhang mit der dann aktivierten Störungstätigkeit im Mittelmeerraum, die

auch noch bis in die östliche Hälfte von Süddeutschland übergreift (Bayerischer Wald, Alpenvorland). Im nordwestdeutschen Küstenraum findet das auf den Februar fallende Maximum von Bremerhaven seine Erklärung ebenfalls aus den Häufigkeitstabellen der niedrigen Bewölkung. Mit steigender Sonnenhöhe und zunehmender Erwärmung nehmen die Nebelblagerungen zu den Sommermonaten hin stark ab und verzeichnen ihr Minimum zugleich in den Monaten grösster Sonnenscheindauer, im Nordwesten im Mai und Juni, im Süden im Juli und August.

Mit diesem Jahresgang liegen die auf das Winterhalbjahr (X. — III.) entfallenden Nebelzuschläge um ein Mehrfaches höher als im Sommerhalbjahr (IV. — IX.). In den Sommermonaten als der Vegetationszeit wird diese zusätzliche Wasserspende, die in den norddeutschen Bergländern sich von 16 % des Freilandniederschlags (ca. 90 mm) in den mittleren Lagen bis auf 100 % (ca. 700 mm) in den höheren Lagen steigert, mindestens bis zu einigen hundert mm von den Pflanzen verbraucht oder verdunstet. Für den Waldbau spielt dieser sommerliche Anteil in Lagen über 500 m im norddeutschen Raum, über 650 m im süddeutschen und über 1000 m im Südosten eine mit der Höhe zunehmende Bedeutung. Hydrographisch dürfte eine Einfluss des sommerlichen Nebelniederschlags erst in Lagen über 700 bzw. 1000 bzw. 1200 m ins Gewicht fallen, soweit grössere Areale in diese Höhenzonen fallen.

Die um das 2,3- bis 3.5-fache höheren winterlichen Nebelzuschläge fallen dagegen hydrographisch viel mehr ins Gewicht. In einer Zeit, wo der Wasserbedarf der Vegetation und die Verdunstung erheblich reduziert sind, stehen im nordwestdeutschen Raum schon ab 500 m 200 mm zusätzlich zur Verfügung, die sich bis zur Höhe des Feldberges auf 700 m, und auf der Wasserkuppe auf 1200 mm steigern. Diese Beträge fallen in dieser Höhe sicherlich nur in den Luv- und Gipfellagen an, während die Leelagen geringere Beträge ablagern dürften. Der auf diese Höhenlagen entfallende Flächenanteil ist im Gebiet nördlich des Mains gross genug und weist genügend ablagernden Waldbestand auf, um für die Auffüllung der Bodenfeuchte und die Wasserbilanz bedeutsame Mengen zur Ablagerung zu bringen.

Im süd- und südostdeutschen Raum bleiben die winterlichen Zuschläge entsprechend geringer, in der Schwäbischen Alb bei 300 mm, im Bayerischen Wald bei 600 mm. Die verhältnismässig geringen Zusatzmengen vom Hohenpeissenberg (220 mm) lassen die Bedeutung der relativen Höhe über dem umliegenden Gelände erkennen, die hier mit nur 150 — 250 m Erhebung eines isolierten Berges zu gering ist, um eine stärkere eigenbürtige Stauwirkung hervorzurufen. Um so höher fallen die Ablagerungen des Winterhalbjahrs im Velebit in 1620 m, unmittelbar in Küstennähe der Adria, mit 2 600 mm aus, wo im Dezember und Januar zusätzlich mehr als das Vierfache der Niederschlagsmenge abgelagert wird.

Messungen, die eine Erfassung des Nebelniederschlags in seiner Gesamtwirkung auf Waldbau und Wasserwirtschaft zum Ziele haben, sollten wegen der jahreszeitlichen Verteilung und des wesentlich stärkeren Anfalls der Ablagerungen im Winterhalbjahr auch diesen Zeitraum einschliessen.

7. Einfluss der Wetterlage auf die Ergiebigkeit.

Die meteorologischen Bedingungen, die zu ergiebigen Ablagerungen führen, werden durch die jeweilige Wetterlage gesteuert. Mit der herangeführten Luftmasse ist deren Feuchtigkeitsgehalt und das Kondensationsniveau, mit dem Stromfeld die Richtung und Geschwindigkeit der ablagernden Luftströmung, mit dem Ablauf des Wettergeschehens die Dauer der Ablagerungen vorgegeben. Die wechselnde Ergiebigkeit der Nebelablagerungen ist an bestimmte Wetterlagen gebunden, für die sich hinsichtlich der einbezogenen Luftmasse übereinstimmende Gesichtspunkte ergeben. Es seien einige typische Fälle auffallend hoher Tagesmengen von Nebelniederschlag

herausgestellt und deren synoptische Wetterbedingungen betrachtet. Datum: RN/R (mm).

(1) *Wasserkuppe (921 m).*

a) 1954. 20.– 21.I.: 150/18. 15.XII.: 44/6. 27.– 29.XII.: 239/38. 28.XII.: 69/6. 3.XII.: 34/2. 3.XI.: 25/0. 1955. 7.– 8.XII.: 99/5. 1956. 10.–14.X.: 45/0. 8.XII.: 46/4.

Hoch oder H-Brücke über Mitteleuropa (HM, BM, Wa) [1]), an dessen Nordflanke gemässigte, maritime Tropikluft (*m*Tp) [2]) oder gealterte Polarluft (*m*Pt) langsam einfliesst. Schwache, höchstens mässige westliche Winde.

b) 1956. 3.– 6.XII.: 33/4, 94/10, 73/2, 70/10. 5.– 7.XI.: 40/11, 27/4, 31/2. 21.1.: 26/1. 1954. 4.IV.: 72/12. 21.I.: 124/16. 2.X.: 48/8.

Hoch über W- oder SW-Europa, T über N- oder NE-Europa (Wz, NWz). Von W oder NW einfliessende maritime Warmluft (*m*Tp, *m*Pt). Schwache oder mässige westliche Winde.

Kennzeichnend für die Fälle stärkerer Ablagerungen auf der Wasserkuppe ist die Wirksamkeit maritimer Warmluftmassen, die vielfach im Zusammenhang mit Hochdrucklagen über W- oder Mitteleuropa, aus gemässigten Breiten (Atlantik südlich 50° Breite) entstammend, an dessen Nordflanke herumgesteuert wurden und bei schwachen Luftdruckgradienten aus SW, W oder sogar NW nach N-Deutschland einfliessen. Die Tatsache, dass fast alle Fälle hohen Nebelzuschlags bei schwacher Luftbewegung ablagern, entkräftet die Vermutung, dass hohe Überschüsse durch seitlich aufschlagende Regentropfen bedingt sind.

2) *Kleiner Feldberg/Taunus (807 m).*

a) 1955. 7.– 8.XII.: 25/2.

b) 1954. 27.VII.: 28/6. 13.XI.: 28/6. 1956. 22.–24.I.: 65/16. 4.– 5.XII.: 54/10. 12.– 13.XII.: 64/13.

Antizyklonale oder zyklonale Westlagen wie bei (1) *a*) und *b*).

c) 1954. 26.XI.: 33/4. 8.XI.: 21/4. 1955. 11.I.: 16/2. 15.I.: 25/9. 18.V.: 23/3.

T über Nordmeer oder Trog von N- nach W-Europa (Sa, TrW) steuern maritime Warmluft (*m*T oder *m*P_t) nach Mitteleuropa.

Maritime Warmluftmassen werden entweder auf der Nordflanke eines westeuropäischen Hochdruckgebiets oder auf der Vorderseite von Tiefdruckstörungen aus gemässigten Breiten, bei Troglagen aus den subtropischen Meeresgebieten nach Mitteleuropa geleitet. Vorherrschende Windstärken 4 — 5 Bft. Zentrale Hochdrucklagen treten nicht mehr in Erscheinung.

3) *Grosser Falkenstein (1313 m).*

a) 1955. 3.– 4.XII.: 37/14.

b) 1955. 16.XII.: 58/10. 28/XII.: 60/14. 1956. 18.I.: 35/13. 2.III.: 42/11. 4.III.: 17/3. 3.VIII.: 12/1. 19.– 20.X.: 44/12. 4.XII.: 47/12. 13.– 14.XII.: 77/14.

Antizyklonale oder zyklonale Westlagen wie bei (1) und (2), *a*) und *b*).

c) 1956. 25.V.: 31/12. 9.– 10.VI: 44/23.

Troglagen wie bei (2) *c*).

d) 1956. 4.VII.: 7/1. 11.XI.: 9/1.

An der Westflanke eines blockierenden H über W-Russland-Skandinavien biegt die atlantische Frontalzone über Mitteleuropa nach Norden um (Ww). Zufuhr tropisch-maritimer Luftmassen.

1) Grosswetterlagen nach: P. Hess and H. Brezowsky, Ber. Dt. Wetterd. US-Zone Nr. 33 (1952).

2) Luftmassen nach: R. Scherhag, Neue Methoden der Wetteranalyse und Wetterprognose. Berlin 1948.

Der Bayerische Wald als ein von NNW nach SSE streichendes Randgebirge empfängt seine ergiebigsten Ablagerungen mit SW-W-Strömung, wenn tropisch-maritime oder maritime Luft gemässigter Breiten auf den Südflanken tiefen Druckes in breiten Strom S-Deutschland überflutet. Diese Wetterlagen bedingen bei d) schwache, bei c) schwache bis mässige Luftbewegung, bei a) und b) auch frische bis stürmische Winde.

4) *Hohenpeissenberg (960 m).*

b) 1955. 26.XII. : 19/10. 28.XII. : 13/7. 1956. 4.III. : 29/19. 14.IX. : 52/17.

Die Fälle zyklonaler W- oder NW-Lagen treten hier viel seltener auf und zeigen eine geringere Ergiebigkeit.

c) 1955. 11.– 14.XI. : 24/3.

Auch die Troglagen treten zurück. Die Ablagerungen werden durch Mittelmeerluft hervorgerufen, die, um die Alpen herumgeführt, von E her anströmt.

e) 1955. 24.– 25.I. : 7/0. 1.– 2.III. : 5/1. 14.– 15.X. : 13/0. 1956. 6.– 7.I. : 10/0. 23.– 26.II. : 12.0. 14.XI. : 10/0. 19.– 22.XI. : 10/0.

Hoch oder H-Brücke über Mitteleuropa, T über Oberitalien bzw. Südostraum steuert auf dessen Südflanke gealterte Polarluft aus SE um die Ostalpen mit E-Strönmug nach S-Deutschland ein. Keine Niederschläge, ergiebige Ablagerungen.

f) 1955. 9.– 10.VII. : 122/68. 1956. 1.V. : 22/10. 12.VII. : 43/20.

Typische NE-Lagen mit hohem Druck von SW durch Mitteleuropa nach Fennoskandien und V_b-artige Störungen im Mittelmeer- und SE-Raum bei gleichzeitig ergiebigen Niederschlägen.

Gegenüber den zuvor besprochenen Stationen nimmt der Hohenpeissenberg eine Sonderstellung ein. Statt der Nordflanke steuert jetzt die Südflanke hohen Druckes feuchtwarme Mittelmeerluft ein, deren Zustrom durch tiefen Druck im Mittelmeerraum, häufig vom Charakter einer Vb-Störung, gefördert wird. Bei gesteigerter Niederschlagstätigkeit wird zugleich ein zwei- bis dreifacher Betrag an Nebelniederschlag abgelagert. Auch nach Aufhören der Niederschläge werden aus der noch anhaltenden Staubewölkung bis zu 2 — 3 mm/h und 10 mm/Tag abgelagert. Soweit nicht tropischmaritime und maritime Polarluft gemässigter Breiten gem. b), c), f), beteiligt ist, findet gem. e) eine Zufuhr von gealterter Polarluft aus Südosteuropa (cP_t) statt, ohne dass es noch trotz ergiebiger Ablagerungen zu Niederschlägen kommt. Für alle Fälle ist schwache Luftbewegung kennzeichnend.

Zusammenfassend kann als wettermässige Voraussetzung für das Auftreten ergiebiger Ablagerungen von Nebelniederschlag die Wirksamkeit maritimer Warmluftmassen aus subtropischen oder gemässigten Breiten angesehen werden. Auch über dem Kontinent gealterte Tropikluft, die keine Niederschlagstätigkeit mehr auslöst, kann in Staulagen noch zu erheblichen Ablagerungen führen. Stärkere Luftbewegung steigert die Ablagerungen, ist aber nicht Voraussetzung für deren Ergiebigkeit.

8. Wolkenphysikalische Einflüsse auf die Ergiebigkeit.

Wenn die Ergiebigkeit des Nebelniederschlags so weitgehend von der ablagernden Luftmasse abhängt, so müssen sich auch Beziehungen zur Mikrostruktur der Wolken ergeben. Dieser Frage wurde mit der Aufnahme von Tropfenspektren nach dem von Diem ([18]) angegebenen Verfahren des unmittelbaren Auffangens auf Träger zwischen zwei Oelschichten und mikrophotographischer Fixierung des Befundes nachgegangen. Aufgenommen wurde bei verschiedenen Nebellagen, ohne Rücksicht auf die Ablagerungsmenge. Die bei insgesamt 25 Messreihen mit je durchschnittlich 12 Aufnahmen und je einigen Hundert bis Tausend Tropfen aufgefundenen Häufigkeitsverteilungen der einzelnen Tropfengrössen lassen sich nach Typen des Tropfenspektrums ordnen.

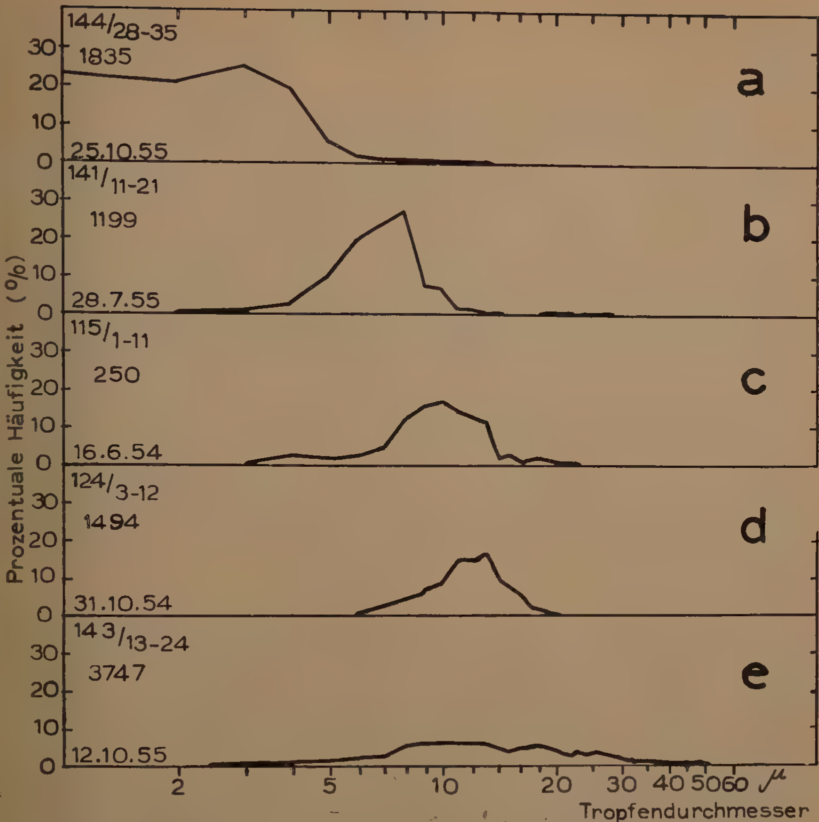


Abb. 2 — Typen der Häufigkeitsverteilung von Tropfengrössen im Nebel.

Jede dieser Gruppen zeigt deutliche Beziehungen zu den Luftmassen und damit zur Ergiebigkeit der Ablagerungen. Als wichtigste Typen in Bezug auf das behandelte Problem treten die in Abb. 2 dargestellten Verteilungen auf.

a) Schmales Spektrum bis max. 10 — 12 µ mit Maximum bei 2 — 3 µ. Kennzeichnend ist der hohe Anteil kleinster Tropfen mit 1 — 2 µ ø oder kleiner.

Wetterlage: Einbruch polarmaritimer Kaltluft bei antizyklonalen Nordwestlagen (25.10.55) oder auf der Rückseite eines abgeschlossenen Tiefs über Mitteleuropa (25.8.54). Ergiebige Niederschläge, mässige Nebelablagerungen

b) Schmales Spektrum zwischen 2 und 15 µ mit Maximum bei 8 — 9 µ, einzelne Tropfen bis 30 µ. Bei meridionaler Zirkulation wird kontinentale Kaltluft aus dem NE-Raum eingesteuert (28.VII., 25.VIII.55). Schauerartige Niederschläge, nur geringfügige Nebelablagerungen.

c) Schmales Spektrum zwischen 5 und 15 µ, auslaufend bis 3 und 30 µ, mit Maximum bei 8 — 10 µ. Bei zyklonaler Nordostlage wird maritime Warmluft aus dem Mittelmeerraum eingesteuert (21.– 22.VIII. 54). Anhaltende Niederschläge, mässige bis ergiebige Nebelablagerungen.

d) Schmales Spektrum zwischen 6 und 20 µ mit Maximum bei 10 — 14 µ. Bei

zyklonaler Westlage löst tropisch-maritime oder Warmluft aus gemässigten Breiten die Staulage aus (31.X.54). Nur geringfügige Niederschläge, ergiebige Nebelablagerungen.

e) Breites Spektrum zwischen 5 und 40 μ, einzelne Tropfen bis 70 μ, mit flachem Maximum bei 8 — 20 μ, zu grossen Durchmessern hin langsam abfallend. Bei hohem Druck von SW– über Mittel– nach Osteuropa wird gealterte Warmluft aus SE oder dem Mittelmeerraum nach Süddeutschland gesteuert. Keine oder nur geringfügige Niederschläge, ergiebige Nebelablagerungen. Das Anwachsen der Tropfengrössen hat MAHROUS ([19]) als typische Alterungserscheinung bei den dichten Küstennebeln in NE-England nachgewiesen.

Zusammenfassend ergibt sich : Polare Kaltluft, durch das Überwiegen kleiner Tropfendurchmesser gekennzeichnet, bringt nur geringfügige Nebelablagerungen zustande. Je höher der Anteil grösserer Tropfen und je breiter das Spektrum, wie es für Warmluft aus gemässigten oder subtropischen Breiten kennzeichnend ist, desto ergiebiger lagern sie ab. Im ersteren Falle besteht eine meridionale Zirkulation, während die Fälle stärkerer Nebelablagerungen überwiegend bei zonaler Zirkulation gegeben sind.

Die unterschiedliche Ergiebigkeit der nach den Typen des Tropfenspektrums geordneten Nebelfälle wird verständlich, wenn man den Wassergehalt der einzelnen Tropfengrössenklassen berechnet, wie er sich aus dem Produkt Häufigkeit $x \pi/6\ D^3$ ergibt. Mit wachsendem Tropfendurchmesser zeigt das Wassergehaltsspektrum auch bei geringer Häufigkeit dieser Grössen schnell wachsende Beträge an. Über das gesamte Spektrum integriert, ergibt sich für die einzelnen Proben

bei Typ	a	b	c	d	e	
ein Gesamtwassergehalt von	2,8	22,8	75,9	105,0	472,8	10^{-6} mm³.

Da die Fälle mit breitem Spektrum und höherem Wassergehalt überwiegend den Staulagen entsprechen, bei denen keine nennenswerten Niederschläge fallen, wird auch aus wolkenphysikalischen Gründen belegt, dass ergiebige Ablagerungen von Nebelniederschlag nicht an ergiebige Niederschläge gebunden sind.

Zu danken habe ich für die Einrichtung einer Messtelle auf dem Tafelberg dem Direktor des Weather Bureau der Südafrikanischen Union, Herrn Dr. Schumann, und für die Betreuung dieser Station Herrn Dr. Nagel, für die Überlassung von Messergebnissen Herrn Meteorologen Kirigin, Hydrometeorologischer Dienst von Kroatien, und Herrn Forstassessor Bauer, Forsteinrichtungsamt Koblenz.

LITERATUR

(1) TROLL, C. : Studien zur vergleichenden Geographie der Hochgebirge der Erde. 23. Hauptversamml. Ges. von Freunden und Förderern Univ. Bonn 1940 (1941).

(2) GRUNOW, J. : Nebelniederschlag. Bedeutung und Erfassung einer Zusatzkomponente des Niederschlags. *Ber. Dt. Wetterd US-Zone*, Nr 42, 30 (1952).

(3) GRUNOW, J. : Bedeutung und Erfassung des Nebelniederschlags. *UGGI. Ass. Int. Hydrol. Sci. Assemblée de Rome* 1954. T. I, 402-415 (1956).

(4) GRUNOW, J. : Kritik des Nebelfängers. Zür Methode der Messung des Nebelniederschlags. Techn. Mitt. Instrümentenwesen Dt. Wetterd. Neue Folgc Nr. 4 (1958).

(5) NAGEL, J. F. : Fog precipitation on Table Mountain. *Quart. Journ. R. Met. Soc. 82*, 452-460 (1956).

(6) SCHUMANN, T. E. W. : Watervoorsiening vir Kaapstad uit die wolk op Tafelberg. *Tydskr. Wet. Kuns. Bloemfontein, 4*, 58-61 (1943).

(7) OURA, H. : On the Capture of Fog Particles by a Forest. In : T. Hori, Studies on Fogs. Sapporo, Japan (1953) 239-259.

(8) GRUNOW, J. : Der Niederschlag im Bergwald. Niederschlagszurückhaltung und Nebelzuschlag. *Forstw. Centralbl. 74*, 21-36 (1955).

(9) ALBRECHT, F. : Wolkenuntersuchungen und Rauhreifbeobachtungen auf dem Sonnblick im Sommer 1926. 35. Jahresbericht Sonnblickverein 1926, 25-28, Wien (1928). — Theoretische Untersuchungen über die Ablagerungen von Staub aus strömender Luft und ihre Anwendung auf die Theorie der Staubfilter. *Physikal. Z.* 32, 48-56 (1931).

([10]) Troll, C. : Die Lokal winde der Tropengebirge und ihr Einfluss auf Niederschlag und Vegetation. (Studien zur Vegetations- und Landschaftskunde der Tropen III). Bonner Geogr. Abhandl. Heft 9 (1952).

([11]) Troll, C. : Wüstensteppen und Nebeloasen im südnubischen Küstengebirge. *Z. Ges. Erdkunde Berlin.* 241-281 (1935).

([12]) Nagel, J. F. : Newelneerslag. Weather-Bureau Pretoria News Letter No. 84 (1955). Water Supply in South Africa. News Letter No. 89 (1956).

([13]) Isaac, L. A. : Fog drip and rain interception in coastal forests. *Forest research Notes* Nr. 34, 1946, Pac. NW. For. Exp. Sta.

([14]) Serra, L. : Interprétation des mesures pluviométriques. Lois de la pluviosité. *Mém. et Trav. Soc. Hydrotechn. France, 2,* 141-155 (1952).

([15]) Linke, F. : Niederschlagsmessungen unter Bäumen. *Meteor. Z., 33,* 140-141 (1916); *38,* 277 (1921).

([16]) Dreyling, H. : Das Auftreten von Bergnebel in Abhängigkeit von der Windrichtung. *Wiss. Abhandl. R. f. W., 2,* Nr. 5 (1936).

([17]) Baumgartner, A. : Zur Höhenabhängigkeit von Regen- und Nebelniederschlag am Grossen Falkenstein (Bayer. Wald). *UGGI. Ass. Int. Hydrol. Sci. Assemblée de Toronto* 1957.

([18]) Diem, M. : Messungen der Grösse von Wolkenelementen. *Meteor. Rdsch.* 1. 261-273 (1947).

([19]) Mahrous, M. A. : Drop sizes in sea mists. *Quart. Journ. Roy. Meteor. Soc., 80.* 99-101 (1954).

CONDITIONS OF THE FORMATION OF UNDERGROUND WATERS IN DESERTS

V. N. KOONIN (URSS)

SUMMARY

1. In studying conditions and ways of nourishment of underground waters in deserts there becomes obvious a clear cut dependence of the first aquifer on geographical conditions. This dependence decreases with transition to deeper aquifers.

The deep pressure waters which are supplied in regions far away from the desert and get to deserts by an underground runoff, can reflect but slightly or not reflect at all desert influences upon their regimen, mineral composition, etc.

The necessity of understanding hydrogeological peculiarities of a desert makes it necessary to study firstly waters influenced by geographical conditions of the desert. This is important from the practical point of view as very often other waters are unaccessible.

2. There are no universal indications how to divide waters into deep and less deep, i. e. in waters with or without «desert» features. Thus, on alluvial plains with thick friable sandyclay accumulations only the first usually «many-storeyed» aquifers with free surfaces can be considered as «headwaters».. In lowland regions «headwaters» should include a whole complex of aquifers, beginning from upper ravins to local artesian wells.

Thus, the division into «near» and «deep» waters is determined by local structural, lithological and geomorphological features.

3. Nourishment conditions for underground waters in deserts are very different from those of any other climatic region. This difference depends on the sort of receipts of the water balance: e. g. in stony deserts the importance of direct infiltration of precipitation sharply increases; in clay deserts the influence of this factor is reduced to zero; on the border between sandy and clay deserts the importance of water infiltration from ephemeral lakes sharply increases; in sandy deserts, of special importance is a condensational accumulation of moisture.

The expenses of the water balance are also different. In contrast to non-desert regions, evaporation from a watertable surface (a capillary rim) at any depth, and its transpiration become of great importance.

4. There are two types of soil formations in deserts of Central Asia:

a) lowlands and alluvial plains mostly located at lowland subsidences and platform margins;

b) «structural» plains, mainly regarded as platforms.

The first are characterised by the presence of thick friable accumulations where ground waters with free surface and nourished from distant sources are widely spread; the salting of the underground waters is insignificant, the local supply in the whole water balance is relatively small but its practical value is extremely great as it is a source of good fresh water of a lens type on the basis of highly mineral waters. Piedmonts and alluvial plains usually separate mountains and «structural» plains. The latter are characterised by the presence of consolidated marine of metamorphic rocks with numerous aquifers with similar structure and small extention.

The local supply is prevalent, whereas the distant one is of least importance. The water composition is extremely various.

5. The accumulation of underground waters resources and change of the chemical composition of these waters present two sides of one process.

To understand the process they should be considered simultaneously.

The nearer are the waters to a supply source, the less they are salted; the longer

is the water's route, the more they are salted. The extent, type and taste estimate of salting are related to each other.

6. The less salted is the water, the more various is its ionic composition; the more salted it is, the more monotonous and standard becomes the chemical composition of the waters. For salted underground waters (not for brines) in deserts, the most typical is a NaCl mineralization, often $CaCl_2$.

7. Rocks on the water's route have a certain influence on the water composition, especially at initial salting stages. But the main influence upon the chemical composition of the underground waters is effected by general factors independent of the composition of rocks. Among them is an interground evaporation providing for a continuous growth of concentration and natural alternation of salting types. On this general background the rock influence changes but slightly the general tendency mentioned above (except cases with haloid rocks).

8. Peculiarities and specification of methods of study of underground waters in deserts.

Report

This report is based on thoughts and data obtained from the study of desert regions located between the Caspian sea and River Amu-Darya, where the author has worked since 1928.

The nature of ground water in the desert is first of all shown in the characteristic structure of the elements of water balance, in particular, in the unusually great and often predominant significance of evaporation amidst the other points of discharge. As a consequence a high degree of salinisation of ground water of the desert takes place and this is well known to all specialists and water explorers. For this reason we ought to do everything possible to reveal the depth of this phenomena in ground waters.

When we deal with deep waters, we see that in the desert are found head waters of every kind of salinisation, that is from fresh to a high degree of mineralisation, as in any other geographical zone. If we deal with the primary waterbearing horizon, e.g. groundwaters, which in the majority of cases are free (unconfined) surface, we see that that horizon reflects the specific conditions of the desert. It is revealed not only highly salinated ground waters but also by the presence of unusual varieties of size, degree and type of mineralisation. Characteristic feature is the fact that in one water-carrying horizon may be found in close juxtaposition highly mineralised chlorido-sodic and sweet hydrocarbonate-calcium waters. The other particular feature of the desert is generally the large thickness of the zone of aeration, which in places reaches 50 to 100 and more m, figures that are rare for zones other than desert.

Thus, in trying to estimate the hydrogeological character of the desert we ought to distinguish sharply between adjacent waters, subjected to great influences of natural conditions of the given location, from deep waters, feebly not at all subjected to these influences.

The question arises: where should we draw a line between the above mentioned types of water. The analysis of hydrogeological data for broad territories of Middle Asia, where different types of deserts are to be found, both by composition of rocks, which form the surface and by physiographic and structural particularities, shows us that we cannot give an universal answer.

Let us take some examples:

To the east of Karabogazgol, between the Usturt Plateau and the Karakum Depression is located the Tuarkyrsk region. Geographically it is a desert; from the

structural point of view it is a miniature folded land with a system of brachianticlinals and sinclinals; from the physiographical aspect—it is a system of small, sharply cris-crossed ridged cuesta type with solonchak depressions in between. Its geological cross-section is characterised by considerable lithological variety and numerous water-carrying horizons of various stratigraphic timing. Here we find ground waters with free surface in loose deposits, the sources breaking through crтks, head waters in different rocks forming small artesian basins, etc. The distinguishing particularity of the water balance of this region is the fact that its intake is determined by atmospheric precipitations typical for the region itself. Total outcome is determined by evaporation and transpiration. Thus, the water does not reach the region either by surfacial or by subsoil drainage and does not leave its limits. In spite of the variety of the rocks and various conditions of the location and also the drainage of ground water — all are scarce and highly mineralised. Exceptions can be pointed out, those are small sweet lenses under those plots where rain waters accumulate temporarily. Since all or almost all water-carrying horizons receive the supply singly from the local feeding territories, all waters are definitely subjected to geographical conditions, e.g. high evaporation, considerable soil salinisation process at the catchment basins; they all, regardless to what rocks they saturate, what depth they reach and what head they have carry clear-cut features of desert influence.

Adjacent to the Tuarkyrsk region lie the large sand planes of the Karakum depression, formed out of sandy clay layers, with greatly developed thick (hundreds of metres) water bearing horizon with free surface. The water of this underground flow fundamentally fed by far distant underground inflow which reaches the region from outside. Since the waters move in the primary free water-carrying horizon, they are subjected to strong evaporation process and transpiration. In spite of the fact that the feeding territories send less mineralised waters, predominantly hydrocarbonate ones which flow along the non-salinised, well washed out, alluvial quartz fieldspatic sands of the Karakum formation the waters are very quickly salinized and become chlorided and highly mineralised short distances away from the feeding territories. In those parts of the desert where the local feeding takes place (for example due to the flow of athmospheric waters from clay parts of the desert and infiltration of these waters up to the water table of salt ground waters), floating fresh water lenses are formed.

Ground waters of the Karakum formation lay on thick clay layers, creating a certain isolation. Lower down lie water carrying horizons, which are fed by the regions outside the desert. The influence of geographical conditions of the desert on these deep waters is not revealed or at any rate is considerably weakened. The properties of this water are determined by the conditions and circumstances of the inflow from the far-distant regions, the hydrodynamical situation depending on the drainage conditions and lithological particularities of the rocks. Here could be found sweet or salty waters independantly of the influence of the modern geographical conditions. Thus, even the second water bearing horizon may be here deprived of the specific hydrogeological features of the desert. The latter may reveal themselves in a way because between the primary and lower horizons to a certain extent water exchange takes place.

These two examples are to a certain extent extreme ones. In the first example the waters of several water carrying horizons, including the local artesian basins, are the product of the desert and they are unavoidably subjected to the influence of local conditions; in the second example, this influence is spread only to the primary water carrying horizon and all the deeper waters may be of the same kind as in any other climatic zone.

We wise to show by these examples the fact that the division of ground waters in the desert along vertical cross-section into waters with specifically «desert»

properties, and into waters lacking them, has no universal signs. We need to apply individual analysis according to each natural region in connection with the ways and means of feeding, physiographical and structural lithological particularities.

From this derives the necessity to establish what is the essence and what is the pressure of the desert on the waters of this character. The researches by V.A. Priklonsky into the plains of Eastern Trans-Caucasia (1930,1932,1946,1948) as well as our researches in the deserts of Trans-Caspian regions (1944, 1947, 1948, 1949) permit us to state the following. The main sources of ground water supplies of the desert are:

1) the losses from surface streams along the beds which cross the desert or bring their water to its edge;

2) subsurface drainage from mountain systems, adjacent to the desert;

3) atmospheric precipitations;

4) supply of deep waters.

Applying all this to the Karakum (Kunin V.N., 1947):

1) Filtration from rivers Amu-Darya, Murgab, Tedgen and small streams of Kopet-Dag. All those, except the mighty Amu-Darya, are exhausted at the edge of the desert; 2) underground inflow, originating inside the bedrocks of Kopet-Dag predominantly from mesozoic limestones and sandstones and flowing through deposits of piedmont plain; 3) atmospheric precipitations; their significance in feeding the ground waters is far from being clear from the quantitative point of view, though it is apparent that it is localised on one hand by the bare sandy areas which are rare, and, on the other hand, by clayish water catching plots (so called Takyr), where the local surface runoff is formed and accumulated; 4) inflow of ascending headwaters strictly limited by the regions of tectonic disturbance; concerning the feeding of ground waters by excess head waters from artesian horizons through divisional water tight layers, we can say that this source cannot yet be considered owing to lack of information and data.

If we exclude the ascending feeding from deeper horizons, which undoubtedly has no essential significance in the total balance, we can see that all other sources bring slightly mineralised hydrocarbonate water.

Independantly of the depth of the water table and compositions of the rocks in which the waters flow on their way, they become more mineralised with predominance of HCO_3' that changes to predominance of SO_4'', then with the growth of mineralisation, to Cl'. Chloride waters with slight exception are sodium waters, while the predominent cations of hydro-carbonate and sulphate waters may be represented in regard to the ways of feeding by $Na^{\cdot}$ and $Ca^{\cdot\cdot}$ The predominance of $Mg^{\cdot\cdot}$ is much rarer.

The direction of the change in the type of mineralisation of water $HCO_3' \leftrightarrows SO_4'' \rightarrow Cl'$ which has been referred to explained by the correlation between solubility and limit of saturation reached by certain compositions according to the growth of concentration. As a result ground water loses first carbonates of calcium, then sulphate of calcium. Both in various modifications are broadly represented in the zone of aeration including the case of lying above present or former water table.

At the estuary distances of the flow of ground water, before the considerable concentration and metamorphisation begins, their composition may be greatly variable. This is determined by broad diapazons of potential solution of various salts, since the concentration of solution is minor (Koolakov, 1955). The most typical for this period is, as we have pointed out, the predominance of HCO'_3. The initial salinisation, under this situation, is considerably influenced by the composition of the rock with which the water comes in contact.

By the growth of concentration the type of mineralisation is «standardised» and the composition of the rock exercises less influence on the composition of the

water since higher concentration makes the possibility of solution of various salts more limited, with the exception of several which are the components of the rocks.

According to our observations highly mineralised ground water of the desert (when concentration is 20-30 gr/l) are predominantly chloride of sodium in any rock. It does not follow however that the rocks have no influence on the composition of waters after the primary periods of metamorphisation. Thus, for example, in the Tuarkyrsk region mentioned above, on water catchment area territories gypsum has been widely spread. It forms the distinguishing mark of the composition of all the waters in the region: the «sulphate» period of metamorphisation is long and the waters obtain a predominantly chloride of sodium composition only with rather greater concentrations. In one of the regions of northwest Karakum water-bearing rocks appear to become dolomite limestones; in this region amidst cations there is a sharp growth of $Mg^{\cdot\cdot}$, but in the neighbourhood behind the borders of the region down the underground flow the predominant element becomes $Na^{\cdot}$. Thus the composition of the rocks to a certain extent changes the composition of the waters, lengthens and shortens certain periods of metamorphisation, but is unable to change the main course of the process of metamorphisation which is determined by the growth of concentration and unilateral change of the types of mineralisation of the water (we are not dealing with the influence of saltbearing rocks, undoubtedly capable of much greater influence on water composition).

Equally impossible is any significant influence of this kind performed by ion exchange reactions between the solution and the water. For water-carrying horizons formed by sands, as for example, the vast territory and cross-section of underground flows of waters in the Karakums, saturating alluvial sandy thick layer, this process may be considered as insignificant. Moreover, this process cannot accelerate the growth of concentration from quota gr/l to tens gr/l, which is observed in a distance of a few dozen of kilometers.

What are then the reasons, which cause the growth of mineralisation?

V.A. Priklonsky considers the main reason for mineralisation to be the evaporation of ground waters, but only with depths which do not exceed capillar ones. With greater depth of water tables the growth of salinisation of ground waters, if it reveals itself all together, ought to be determined by other causes, in particular by the interaction with rocks.

We have come to conclusions that the evaporation from surface of water table takes place at any depth and this process is the main one determining, the growth of concentration of ground water in the desert (1944,1947,1948).

The foundation for this conclusion we find are the following indirect circumstances:

If we do not accept the process of interior evaporation at any depth of location of the water table, it is impossible to imagine where goes the water, which feeds the ground waters of Karakums in different ways, since the territory of location in which ground water is located at smale (capillar) depth e.g., is not generally large. The evaporation from this territory only cannot balance the inflow, but at the same time there exist no other ways for discharge except evaporation and transpiration.

The total feeding of ground waters in Karakum from different sources is estimated at a figure approximately a little more than 200 cub.m/sec. The evaporation off the territories where table layer is located at capaillar depth is considerably less than 200 cub.m/sec. The transpiration in these sectors is very small, since there are mostly solonchak soils with extremely thinned solonchak vegetation. On the predominant territory of the Karakum desert the root systems do not reach capillar fringe and thus, the loss by transpiration goes on account of the spring rainfalls and intra-ground condensation, that do not reach the water table and that are not counted as income of the water balance.

The major part of the territory of the Karakum desert has a depth of the location of water table considerable deeper than 10 meters. At these depths, in ground water flowing with a velocity of approximately 10-20 m per annum and well-saturated with drained quartz fieldspotic ancient alluvial sands, we notice the growth of salinisation from 1-2 to 20-40 gr/l with transformation of hydrocarbonate waters into sulphate kind and later into chloride type. When it reaches 20-30 g/l the following growth of mineralisation is noticably retarded, —the waters in familiar to us diapozons of salinisation stay chloride type. The following growth of salinisation leads to only gradual growth of aquation $\frac{Cl'}{Na^{\cdot}}$ eq. from the less I to more I.

Since there are no possible processes—except the intraground evaporation—by which these phenomena can be explained, the author had to seek factors, which would prove the intra-ground evaporation.

The hypothesis of the concentration of oil waters on account of deep evaporation may serve as additional prof to us, since there we deal with evaporation, combined with oil gases, that take place, obviously, at the moments of sharp gradient pressure occasions. We talk about the evaporation off the surface of the water table—off capillar fringe into the atmosphere of the rocks outside the process of production and enveloping gases. However we have no right to overlook the works carried out by petroleum geologists (C.W. Washburne, 1914; R.V.A. Mills and R.C. Wells, 1919; W.Z. Russel, 1933; V.A. Soolin, 1935).

The majority of experimental works especially those published in the U.S.A. point to the fact that with the growth of distance from the ground surface up to water table the amount of the evaporation of the ground waters sharply decreases. But we could not find any works that mention that the decrease comes down to O.

We have no reason, deriving from theoretical position, to deny the possibility of intra-ground evaporation at any depth of location of the water table. As A.F. Lebedev's works (1936) show, with relative humidity of intra ground atmosphere close to 100% (which is actually observed at the depth we are interested in) the mobility of water vapour goes on according to a temperature gradient from the place of high temperature to the place of low temperatures. In isotermic conditions the mobility takes place according to gradient of pressure. F.F. Kolyasev (1946) shows that the temperature gradient has greatest significance for the replacement compared with other factors. Deriving from this point of view the water vapour ought to move upwards from the water table to the belt of constant temperatures. In the desert of Trans-Caspian territory including the Karakum the areas with the water table located deeper than constant temperature belt is estimated at hundreds of thousands sq klm. Naturally, the direction of mobility of water vapour above the belt of constant temperatures ought to be subjected to seasonal influence.

The evaporation off the water table at considerable depths of its location obviously cannot have an essentially absolute significance. Deriving from the approximale data of the tables of the water balance of the Karakum desert we may talk about the annual layer of evaporation off the water table that is measured 1 cm or fractions of it. In spite of the not very large specific value of this process its significance is determined by the fact that it is spread over a huge territory and acts constantly, since in desert conditions there exists a gas penetrating zone of aeration.

Since within the process of capillar ascedance and evaporation the concentration develops and grows (B.B. Polynov and Filosofov, 1930; B.B. Polynov, 1932; B.B. Polynov and Bystrov, 1956), less soluble salts precipitate, forming intra-ground solonchaks (V.V. Dokuchaev, 1899; B.B. Polynov, 1934). They are located above the water table and mark the present and former location of the water table as well, offering the data for paleo-hydrogeology (V.N. Koonin, 1947, 1948).

C. Therzagi in a booklet edited by Meinzer O.E. points out the possibility of considerable depth for evaporation in arid conditions. He quotes the work of W.E. Simpson (1934). This point of view is shared by O.E. Meinzer (1942). Recently, with the aim of clarifying the main aspects of hydrogeology of the arid zone, this problem, amidst others, was advanced for discussion by A. Robaux (1953) in his report at the Ankara symposium concerning the programme of arid zone, organised by Unesco. It is a pity that the author was not aware of the existing soviet literature, where analogous questions have been under investigation for a long time.

If one of the basic particularities of the desert is the presence of highly mineralised subsoil waters, the more important particularity of the nature of the desert is the presence of ideally sweet waters, accumulated in form of floating lenses, surrounded with highly mineralised waters.

Let us deal with this question briefly.

All the waters formed in the desert in first horizon create finally floating lenses of fresh water, equation of equilibrium of which are widely known (system Ghyben-Herzberg).

For the analysis of the dynamics of these lenses the formulas of movement stability of ground waters may be used on the analogy of the dynamics of sweet waters and salt solutions of sea coasts worked out by N.K. Girinsky (1949, 1950 1951, 1955). May also be applied these formulas permit us by analysis to determine the volume of the lenses, the hight of the level of the water table of sweet water compared with height of the level of salty waters, and the depth of location of sweet waters for any cross section of the lens encluding the maximal one. For this purpose at the place of studies should be determined the figure of elevation of sweet water table above the salt water table at any cross-section of the lens, and the distance from the fringe of the lens to this point of profile.

In the deserts of Middle Asia three different genetic types of sweet floating lenses are known: takyr, piedmont and subsand.

Takyr lenses. Amidst the sandy desert are spread small clay plots-known as takyrs—in area varying from fractions of one to a few sq.klm. The surface possesses fine watercarying properties, but is distinguished for remarkable smoothness and small slope. Partial rainfalls flow from takyrs into the sand surrounding them, but the main mass of rain water is accumulated and is lost in evaporation. The local population from ancient time collects the water from takyrs by means of shallow ditches and taps the water into artificial basins which suck it up. It descends to the level of the water table from there and forms sweet floating lenses, which are later exploited through the wells. This is one of the ingenious way of creating the artificial ground water, which was applied long before the spreading methods developed in the USA.

The observation showed that according to a character of takyr water accumulation process one sq. klm of its surface, with the presence of the small water collecting net may give 15-30 thousand m^3 of annual inflow (V.V. Bogdanov, 1954; G.T. Leshinsky, 1954). These figures approximately are the typical ones for estimating the volume of takyr lenses.

The waters of these lenses are known to be less salinised (0,3 gr/l and higher) and to have composition of definite character.

The less the water is mineralised, the higher the presence of HCO_3' and $Na^{\cdot}$, up to the time of appearence of soda waters, and the less are the presence of Cl'. Lowered down and mixing with ground waters, the presence of Cl' sharply rises, while HCO_3' falls and the water has a standard composition, applied to chloride-sodium ground waters of the desert. For the vertical hydrochemical cross sections

takyr lenses sharp shifts from sweet to salty waters are typical. Thus the change of. the water with mineralisation up to 1 gr/l and less for the waters with mineralisation up to 30 gr/l and more take place within intervals of 0,5 to 1 m in a homogenuous sandy soil.

The calculation of different parameters of takyr lenses satisfy completely the equation of equilibrium. True, in attempts to calculate the capacity of lenses soon after absorption of rain-water, the calculating capacity appears to be much bigger than the real one.

Apparently the equation of equilibrium is just only when this equilibrium is actually established. In this case takyr lenses become close to generally widely known ideal scheme, island lenses.

The diameters of takyr lenses do not usually exceed ten, perhaps a few hundred metres, their thickness as a rule not more than 10 meters.

The total income of waters of the takyr flow off into ground waters on general desert balance is nil. In any case it is much less than the precise calculation of the water balance possible at present. Practically their significance is immense. Sweet lenses spread amidst the «sea» of salty ground water are places of unique and at the same time cheap sources of water supply.

These data concern the conditions where annual precipitations accumulate approximately up to 100 m.m. and 60% of them fall during two to three spring months, the rainless period being from May to October.

Piedmont lenses. Temporary surfacial flow off foot-hills and piedmont plains flowing along the slopes is confronted with mounds neighbouring the sandy desert, and forms ephemeral lakes. Part of the water is sucked in and forms floating lenses. A large part of the water evaporates. Correspondently, the volumes of flow off, the capacity of lenses are estimated by hundred of thousands or millions of cub. meters.

The water of these lenses mineralises rather more than the water of takyr lenses, their chemical composition is more varied. This is explained by washing off process endured by salts, they are washed off from much larger and much more, heterogeneous water-catchment areas.

Owing to the fact that at the point of junction of piedmont plains and neighbouring desert plains exist rather complicated geological conditions (the rocks of different lithological composition endure frequent change-over) the lenses are of rather complicated form too. They lack regular outline in plan and profile. The diffusive layer has sometimes large profiles and complicated stratification. Attempts to calculate the volume of lenses according to equation of equilibrium do not give satisfactory results owing to the fact that this equation does not include numerous and important deviations from the scheme.

Some of the results of the studies of temporary runoff which took place in Western Kopet-Dag may be found V.N. Koonin and M.S. Protassiev (1956) and Leshchinsky (1954). Apparently under the very same quantity of annual precipitations (150-200 mm) and equal distribution temporary runoff, in relief of badland developing in less soils, has minor significance and forms only as a result of rare showers. In badland, developing in clay soils and sandy loam soils, the temporary runoff reaches greatest significance and forms itself practically annually, sometimes several times during a period of seasonal rains even with minor power. All other types of foothill and piedmont desert give mean significance of temporary flow· The conditions for temporary flow off process at piedmont plains are highly favourable. Inspite of the fact that granular-metrical composition of covering formations are much more rough than at takyrs owing to the considerable slope of the surface

of piedmont plain the flow is formed swiftly, but thanks to the territories the volume of flow is large which is important for practical point of view.

An important factor, an element in the calculation of the scheme of the runoff is the value of humidity of soil during the period before the rain falls. Depending on this value the primary losses of the flow vary so much that under certain conditions the powerful rains do not form the flow at all, while under different moistening degree precipitations up to 3 and 4 mm accumulate at the same catchment an amount which has practical significance. This situation has been known for a long time, thus the task for the mentioned researches was to find more or less reliable method of calculation, which permits us to make a step forward from short time observations of the runoff and soil humidity to the calculation of these values during any period according to data of metereological observations. This problem was solved.

The figure of mean annual runoff of foot-hills and piedmont plain flows, when the annual precipitation is 150-200 m.m. and its concentration takes place in cold season, in the absence of rainfall during the hot season, has changed from 13.4 mm per area of catchment $\backsim$17 sq.klm. up to 3,0 — 2.0mm per area of catchment more than 200 sq.klm. (V.N. Koonin and M.S. Protassiev, 1956).

By means of various technical means, sometimes very simple ones, for example, by guiding dams, it is possible to increase considerably the income of the flow at the necessary points and to create comparatively stable sources for water supply.

The role of foot-hill piedmont plain flow in the general water balance of the desert turned out to be very significant but only for the adjacent regions of the mountains. The income part of the water balance of these regions of the desert may well be determined by the above-mentioned flow off process.

Subsand lenses. When we talk about the lenses of dune coastline of the moistened areas nobody doubts the determining role of atmospheric precipitations for the feeding of the ground waters.

Dealing with dry conditions, for example, with the northern zone of the deserts of the USSR, where atmospheric precipitations are about 200 mm per annum, where snow has a certain part to play, all the same close contact between the atmospheric precipitations and the regime of ground waters is revealed without difficulty.

The question arises—do we have a reason to estimate principally the feeding of the ground water in more arid conditions?

When we deal with the Karakum desert, where precipitations are about 100 mm we may well suppose that 50 or 60% are concentrated during the spring season and provide infiltrational moistening as well as feeding for ground waters. As soon as we try to estimate quantitative and at least qualitative connection between these precipitations and the nutrition of the ground water we turn into difficulties. Prominent research work done by A.F. Lebedev established the mechanism or mobility of various types of soil humidity. The full publication post mortem of the authors work in 1936 is apparently unknown beyond the borders of our country. In Middle Asian deserts the ideas of A.F. Lebedev greatly stimulated the revaluation of the problem of the nutrition of the subsoil waters. His main research work, however, concerned the top layers of the sand horizons. Here he had the chance of direct study both of humidity and temperature. The conclusions concerning this small depth we obviously may accept as more or less reliable.

The study of greater depths was limited. From the methodical point of view the research works cannot be accepted as perfect, because direct observations were carried out only for humidity of samples of repeated drilling. The thermal regime was estimated theoretically or based on indirect speculations. This has not yet provided us with fully reliable perfect data. Besides, during these past years the

estimation of humidity dependance between different grades of humidity and thermal conditions has changed and the very same results of the observations permit us to draw different conclusions.

However the results of these researches turned out to be important in one respect. They established that in most regions of the sandy desert of the Karakum gravitational infiltration is absent. Even in barkhan sands the gravitational infiltration is highly limited and takes place when the water table is close to the surface (5-10 meters deep). It takes place too at powerful rainfalls, which are a rarity.

Taking in consideration the fact that on the major part of the Karakum desert the water table level is higher than 10 meters, reaching at places 50-100-200 and more m, the territory of barkhan sands is not large, while no less than 85% of the territory is covered with vegetation, we must admit that infiltration cannot be of essential significance for nutrition of subsoil water of the Karakum desert.

Since, thus, direct study permitted us at the present time to establish only the negative concept that the infiltration of precipitations in most cases does not reach the water table, the more necessary did it become to try and solve the problem in an indirect way. This attempt made us devote our report, based on many years of observations carried out by the author in the Karakum desert and on works published by various scientists, including two devoted women scientists hydrogeologists E.N. Deutch and N.G. Shevchenko, who during several years uninterruptedly carried out researches into ground water of the Karakum desert and organised on the spot the study of the regime of the ground waters.

The sizes of the subsand lenses which are not connected with temporary surface flow off process vary greatly: in area they are either few ten of sq.m or largerth an 1000 sq.km; vertically some are few meters deep or a fraction of a meter, some are several ten of meters. In most cases the lenses through a diffusive layer change into salty water levelling with them in the same sandy water carrying horizon. In some cases we observed true water tight clays. Small lenses are usually found under bare (barkhan) sands, but large size ones accumulate under vegetation-covered sands too.

Studying the small lenses under the barkhan sands we have revealed the following data. The higher are the barkhan forms, the more frequently is sweet water formed under their cover. The area of barkhan sands has no determining bearing from the point of view that unique formations spread amidst vegetation covered sands accumulate the sweet lenses as well. Naturally if the barkhan sand territory is large, the lenses are located frequently and sometimes join together. But the dome of the water table always is fixed under the ascended area of barkhan formations, from where the table has slopes towards the adjacent depressions.

In cases when the depressions have vegetation cover or when the water table lies on the level of capillar fringe and not deeper this distribution of the slopes is easily explained as it is determined by transpiration and evaporation. In cases of deeper location this mentioned distribution of slopes cannot be explained in the same manner. If atmospheric precipitations fed the ground water on account of gravitational moisturing, then this process would be more intensive in places where the distances to the table are short, e.g. in depressions, where the higher location of the table itself could be observed. But since we see an opposite picture, we are obliged to conclude, that gravitational moisturing is not actually taking place and that ground waters are accumulating in some other way. This is good for only one process, the condensation of the water vapour. This make us realise that sweet lenses connected with barkhan sands are found in places where the mass of sandy forms are greatest. These very lenses are the most stable and the largest. At the foundation of some large barkhan formations we found small sweet water springs. The location of lenses showed that their stability is possible under following conditions:

1. If the ground water of given plot has an exit that is, if it can be drainaged more or less intensively. That is why most frequently we meet lenses in those barkhan sands which are located next to relief depressions. The presence of drainage diminishes the possibility of a stagnation of sweet waters, a fact which retards the process of the mixture of water.

2. If the main ground water over which the lense floats are not very salinised.

These rules are by no means absolute laws. We know about lenses covering the waters partly salinised up to ten of gr/l and where a stagnation regime has been established. But these lenses have less capacity and are salinated with insignificant water flow off charge process? The less the salinated ground water the larger the capacity of lenses concerned. This naturally determines the quantatitive interrelations of two differently salinised mixing liquids. When ground waters are salinated 10-20 gr/l the lenses are developing very well in these conditions.

Concerning the large lenses, on area larger than hundred kilometers, we had the very same difficulties as the scientists studying the sweet waters of erg Sahara desert.

All possible hypothesis about the formation of the water have been stated (H. Schoeller, 1945; B.G. Cvijanovich, 1953).

The studies showed that nutrition of large lenses in the central parts of the Karakum desert is not connected with a temporary surface or underground flow off water process which originates in adjacent mountains. Ascending nutrition from the deep horizons absent also appeared to be.

Thus, the lens nutrition from outside hypothesis was excluded. Two hypotheses were left and exist at present time. Some think that the sweet water of the lenses is local fed. Others suggest that is was buried, left since the time of alluvial development of the Karakum desert and consequently that these lenses are doomed to disappearance. The authors of the latter idea, realising that small lenses are formed and infilled at our presence consider that the formation of larger lenses cannot be explained in the same way. We must point out that we have lenses of several cubic klm in volume. If we add to this the total amount of precipitations, more or less 100 mm and half of them are innefficient and do not provide any kind of serious moisturing, the rains fall on the surface of vegetation covered sands and transpiration takes place to a certain extent on account of the same source, it is easy to understand our sceptical attitude to an idea about local nutrition as the main source of nutrition of large lenses. Though we ought to point out that all lenses, small and large, pass through all degrees of transitions.

All lenses have remarkably sweet water and we cannot explain how this water could survive so stable in duration of time, when next to it in the very same climatic and geological conditions ground water is highly mineralised.

On the contrary, with the presence of balanced regime in inflow and flow-off process the possibility for saving a considerable fraction of profile of slightly mineralised water of good quality becomes clear.

The study of the regime of large lenses revealed the following data.

The water table of salinised ground water in vegetation-covered sands beyond the limits of the lenses have annual shift oscillations about 5 or up to 15 cm, frequently even less. The influence of annual atmospheric precipitations is observed only in cases of close location, 5 or 8 meters away from the water table, and with extremely significant but rare rainstorms.

Compared with annual shift oscillations of the water tables of sweet lenses we see that the latter have 0,3 m. The greater shifts are noticed at those plots, where deepest location of the tables are the most characteristic (deeper than 30-40 m) with the presence in the zone of aeration of more or less thick clay inter layers. (We must point out that this conditions would determine the smallest shifts if we accept gravi-

tational moisturing up to the table). The ascendency of the level begins in the autumn or in the winter long before the spring precipitations. We ought to mention that at this level of depth tranpiration is lacking, intra-rock evaporation from the surface of capillar fringe should reveal itself at a maximum, if it exists here, during the winter, since the table lies deeper than the zone of constant temperatures. Most of the year the water table lies the high level, part of the time being stable. With pulsating income of moisture on account of infiltration it would be more reasonable to expect sinosoidal character of the curve.

Observation of the temperatures showed that at the depths where thermometers do not record the temperature changes during the year, the temperature of sweet water is 1-3 gr. higher than the temperature of salty waters. The higher temperature of sweet waters compared with salty ones in equal geological and geothermical conditions of adjacent sectors of location of salinised waters may be explained by emanation of the warmth produced by the condensation of the water vapour. It is necessary to emphasize that to build more sound conclusions we ought to carry out further thorough thermometrical research work, in which we have up to now taken only the first steps. It only remains for us to echo the opinion of the prominent French hydrogeologists H. Shoeller (1941, 1949) and A. Robaux (1953), who underlined the extreme importance of thermometrical research work for understanding the true nature of ground waters of the desert.

Here are some data about the composition of the water. The sweetest ground water of the desert, closely connected by the nutrition with the surface waters, has generally turn out to be hydrocarbonate in character. In cations the predominance sometimes belongs to sodium, if the waters are fed on account of sucked in rainfalls from takyr or calcium, if nutrition falls on account of losses in the river bed. Naturally the mixing of these waters with ground water of different chemical composition leads to a formation of various compositions of water depending on the composition and quantitative equations of primary mixtures. We observed this phenomena in takyr lenses. However it appears, under the barkhan sands in lenses situated close to the ground surface, in lenses formed by direct infiltration, different compositions are formed, determined by various degrees of mixture. The sweetest waters of these lenses, as a rule, are hydrocarbonate, recording their infiltrational origin from precipitations.

The hydrochemical particularities of large lenses, outside direct infiltration, appear to be of different character. Even with a slight salinisation they have chloride of sodium water, sometimes sulphate composition; that means the sweet water of large lenses are characterised by ionic composition similar to the composition of salinised and highly metamorphised ground water of the desert. This fact may be explained evidently only by the fact that the lens is formed on account of condensation, which brings water lacking any salts, and this leads to, predominantly, greater dilution of chloride-sodium ground waters, reserving their fundamental correlation of the components in side formed sweet water. Naturally, because of correlations of different degree of solubility even in these sweet waters the relative role of hydrocarbonate ion is always considerably significant.

The attempt to establish the source of nutrition of condensational water gave birth to three hypotheses.

1. Intra-ground evaporation from the surface of the capillar fringe. This process, apparently takes place in sand desert at a large area of the development of ground waters with free surface, located in the sand water-carrying layer. This process ought to be most stable, theoretically speeking, at the levels of depth which are higher than the depth of the constant temperature, e.g. about 15-20 m or more. The water table of large lenses frequently lies at the depth which is higher than this figure. Since at these levels the humidity of sand rocks is always higher than the maximal

hygroscopic capacity, and usually than the maximum molecular water capacity, then the intraground atmosphere will be saturated with water vapour and the latter will be moving and shifted from the sphere of higher temperatures to the sphere of lower temperatures. It is supposed that at a certain level condensation takes place, predominantly in zone of constant temperature and the reverse income of moisture takes place in gravitational form, which feeds the ground waters. It is easy to guess that sweet water cannot form in such a way. With evaporation the concentration is increasing, with reverse income it is decreasing. The final result will be equal approximately to the primary one and any noticeable distillation would not take place.

2. The ideas of Folger about the income of water vapours into the soil together with the air has been rejected for some time. But A.F. Lebedev showed that water vapour can penetrate independantly of atmosphere into the soil because of the difference in pressure under certain thermal regimes. Minor observations carried out in this respect in the sand desert did not provide definite data. At any rate if there were signs of this process the reliable data of quantitative results are beyond our knowledge. We have relatively no data estimating the possibility of condensational accumulation of the liquid entering in this manner and its further transit up to water table. The above mentioned source is completely hypothetical, but certain facts tell us that the true estimation of the hypothesis has essential significance, even if the results will prove unsatisfactory.

3. Thus, there is left only a single source of nutrition-atmospheric precipitations. If direct observation at the regime of humidity show that by gravitational means moisture can penetrate only through the first metres of the zone of aeration, the other above mentioned data and conclusions show that further passage of the water takes place through vapour forming process and condensation at a certain depth. This process does not take place every where, but at a certain complex of thermal, lithological, and hydrogeological conditions, the intensivity of the process can, depending on these conditions, seriously changing itself.

Considering the subsand lenses of the desert possessing large size (cubic Klm) their role in practical view and in water balance of the desert ought to be important. Nevertheless we have no reliable theory of their formation and this handicaps organisation of their optimal exploitation.

The study of these lenses by the drilling method does not solve the problem of the origin of water resources. The study of the regime of the levels, chemical compositions and temperature of ground water gives advantage for indirect explanations but does not give reliable quantitative figures due to difficulties in estimation the volume of wash off and diffusional mixing. The soil scientists and botanists having achieved eminent results, but do not enter with their methods of research the deeper zone of aeration and the latter appeared to exist not only between the sphere of soil humidity and zone of saturation, but also between different scientific faculties.

The appliance of reliable geophysical methods of research into the whole depth of zone of aeration with quantitative estimates of temperatures up to the tenth and hundredth of degree, with precise calculation of diffusion of vapour, according to gradients of temperature and pressure, with estimates of different categories of humidity, on the basis of all these elements and together with analysis of climatic conditions and other elements of physico-geographical complex, would give us sufficient grounds for a quantitative and qualitative calculation of the process of accumulation and expenditure of sweet water of the sand desert. This is all the more important because there are a number of thoughts that permit us to calculate the possibility of artificial control or at least stimulation of the process of accumulation of water in the desert.

ИСПОЛЬЗОВАННАЯ ЛИТЕРАТУРА

Богданов В. В. — Временный поверхностный сток на такырах. « Пустыни и их освоение ». Сб. II, АН СССР, 1954 г.

Гиринский Н. К. — Грунтовые потоки в однородных образованиях морских побережий. Тр. Лабор. гидрогеол. проблем АН СССР, М., т. 3, 1948 г.

Гиринский Н. К. — Напорный поток пресных вод в однородных пластах морских побережий. Там же, т. 9, 1950 г.

Гиринский Н. К. — К расчету установившегося плоского движения двух потоков подземных вод со свободной поверхностью разной минерализации. Докл. АН СССР, М., т. 80, № 2, 1951 г.

Гиринский Н. К. — Установившийся пресный поток под лесозащитными полосами вдоль крупных ирригационных каналов в районах с засоленными грунтовыми водами. Тр. Лаборат. гидрогеолог. проблем. АН СССР, М., т. 13, 1955 г.

Докучаев В. В. — К вопросу о Репетекских гипсах. Зап. Мин. об-ва, ч. 37, в. II, 1899 г.

Колясев Ф. Е. — О мерах борьбы с испарением почвенной влаги. Научн. отчет Всесоюзн. физико-агроном. ин-та за 1942-1943 г.г. Сельхозгиз, 1946 г.

Кулаков Н. В. — Условия формирования солевого состава подземных вод. Ученые записки Саратовского Госуд. ун-та, т. XLУI, вып. геологич. Харьков, 1955.

Кунин В. Н. — Подземные воды Кара-Кумов. Институт географии АН СССР, 1944 г. Библиография докторских диссертаций 1945 г. Изд. биб-ки им. Ленина, М., 1947 г.

Кунин В. Н. — Происхождение подземных вод Каракумов. ИВГО, 1, 1947 г.

Кунин В. Н. — О глубине физико-географического воздействия в условиях песчаной пустыни. Изв. АН СССР, серия географ. геофиз., 1, 1948 г.

Кунин В. Н. — Задачи изучения режима вод в пустынях Средней Азии. Пробл. Физич. географии. Изд. АН СССР, XIV, 1949 г.

Кунин В. Н. и Протасьев М. С. — Временный поверхностный сток пустыни и его роль в питании грунтовых вод. Доклад, представленный советской делегацией на XX сессию Международного геологического конгресса в Мексике, 1956 г.

Лебедев А. Ф. — Почвенные и грунтовые воды. Изд. АН СССР, 1936.

Лещинский Г. Т. — Сток дождевых вод с такыровидных и сложенных плотными глинами бассейнов. Изв. АН Туркм. ССР, 1, 1954 г.

Лещинский Г. Т. — Расчет объемов дождевого стока с такыров и такыровидных водосборов. Изв. АН Туркм. ССР, 2, 1954 г.

Полынов Б. Б. — Изменения растворов солей при их перемещениях в почве. Природа, 8, 1932 г.

Полынов Б. Б. — Кора выветривания. Изд. АН СССР, Л., 1934 г.

Полынов Б. Б. и Быстров С. В. Об изменении растворов солей, циркулирующих в почвах. Академик Б. Б. Полынов. Избранные труды. М., 1956 г.

Полынов Б. Б. и Философов Б. И. — Об изменении растворов при капиллярном поднятии их в почвах и грунтах. Изв. Научно-милиор. ин-та. Т. XXI, Л., 1930 г.

Приклонский В. А. — Гидрогеологический очерк Мильской степи. Матер. к общей схеме использования водных ресурсов Кура-Араксинского бассейна. В. 10. Тифлис, 1930.

Приклонский В. А. — Гидрогеологический очерк низменности Восточного Закавказья. Матер. к общей схеме использования водных ресурсов Кура-Араксинского бассейна. в. 6. Тифлис, 1932 г.

Приклонский В. А. — Формирование грунтовых вод в заслушливых областях на примере Кура-Араксинской низменности. Изв. АН СССР, серия геологич., 4, 1946 г.

Приклонский В. А. — Некоторые закономерности формирования грунтовых вод в засушливых областях. Тр. лаборатории гидрогеол. проблем АН СССР, т. 1, 1948 г.

Сулин В. А. — Воды нефтяных месторождений СССР. М.-Л., 1935 г.

Cvijanovich B.-G. — Sur le rôle des dunes en relation avec le système hydrologique de la nappe souterraine du Grand Erg. Trav. de l'Inst. de Recher. Sahariennes, t. IX, Alger, 1953.

MEINZER O. E. (Edit.). — Hydrology. Physics of the Earth. vol. IX, N.-Y. 1942.
MILLS, R. V. A. and WELLS R. C. — The evaporation and concentration of waters associated with petroleum and natural gas. U.S.G.S. Bull. 693. Wash. 1919.
ROBAUX A. — Physical and chemical properties of ground water in the arid countries. Proc. of the Ankara symposium on Arid zone Hydrology. UNESCO. Paris, 1953.
RUSSEL W. L. — Subsurface concentration of chlorine brines. Bull. Amer. Ass. Petrol. Geolog. vol. 17, n. 10, Oct. 1933.
SCHOELLER H. — L'influence du climat sur les eaux souterraines vadoses. Bull. Soc. Geol. France. ser. 5, t. 11, n. 7-9 (1941).
SCHOELLER H. — L'Hydrogéologie d'une partie de la vallée de la Saoura et du Grand Erg occidental. Bull. Soc. Géolog. de France, t. XV, Fasc. 7-8. 1945.
SCHOELLER H. — La température des eaux souterraines. Trav. du laborat. geolog. l'Université de Bordeaux, t. 1, n. 1, 1949.
SIMPSON W. E. — Foundation experiences with clay in Texas. Civ. Eng. vol. 4, n. 11, Nov. 1934.
WASHBURNE C. W. — Chlorides in oil-field waters. Am. Inst. Min. Eng. Trans. vol. 48, 1914.

ÜBER DIE KONDENSATION DES WASSERDAMPFES IM BODEN

M. TRÉNEL, H. WEBER UND H. LINDNER,
aus den Instituten für Bodenkunde und Pflanzenernährung
der Humboldt-Universität zu Berlin.

Die Wasserbewegung im Boden folgt nicht allein hydraulischen Gesetzen, sondern die dampfförmige Phase des Wassers sowohl als auch die kolloiddisperse Phase — diese wiederum im Zerteilungsmittel Luft wie auch im Zerteilungsmittel Boden — scheint eine größere Rolle zu spielen als bisher angenommen worden ist.

Auf Grund unserer Untersuchungen über den Einfluß der Grundwasserabsenkung (S. TRÉNEL[34]) sind wir der Meinung, daß die Wasserführung des Bodens durch ein kompliziertes Wechselspiel gesteuert wird, an dem eine ganze Reihe von Faktoren beteiligt sind, wie

Regenhöhe,
Saugdruck der Pflanzenwurzeln und Mikrobionten,
Hygroskopizität der mineralischen und anorganischen Bodenkolloide (Hydratation der verwitterten Silikate und adsorbierten Basen),
Tension des Wasserdampfes in der Bodenluft und seine Herabsetzung in den Bodenkapillaren (Kapillarkondensation),
Kondensation zu kolloiddispersem bis zu tropfbar flüssigem Wasser in den Poren des Bodens,
kapillarer Aufstieg der Wasserfäden,

ein Wechselspiel, das wissenschaftlich noch nicht in allen Einzelheiten übersehen werden kann.

Die meteorologischen Vorgänge spielen sich unsichtbar, aber im verstärkten Maße im Boden ab, indem durch die hygroskopischen Eigenschaften der Ton- und Humusteilchen das im Temperaturgefälle kondensierte Wasser sofort abgezogen wird, so daß die Kondensation dadurch verstärkt wird. Unterstützt wird dieser Vorgang sehr wahrscheinlich ferner durch Kapillarkondensation, die bei gleichzeitiger Erhöhung des Siedepunktes die Dampftension des Wassers erniedrigt. Die Bodenkolloide, Wurzeln und Mikrobionten wirken hier gleichsam wie « Trockenmittel » im Exsikkator. Den auf der Oberfläche gerade kondensierten Wasserdampf nehmen die Pflanzenwurzeln in statu nascendi auf; hiervon leben sie während der sommerlichen Trockenheit.

In *ariden* Gebieten, in denen der Boden an seiner Oberfläche tagsüber in besonders starkem Maße unter seine Hygroskopizität austrocknet, dürfte der Kondensation von Wasserdampf im Boden eine *besondere Rolle für die Versorgung der Pflanzen mit Wasser* zufallen.

Seit der Mitte des vergangenen Jahrhunderts haben sich eine Reihe von Forschern mit diesen Fragen beschäftigt.

Der erste, der sich mit dieser Frage experimentell befaßt hat, war wahrscheinlich GIESELER (8), der die Behauptung von O. VOLGER (40-12), daß das Grundwasser nicht durch Infiltration, sondern ausschließlich durch Kondensation gespeist würde, durch Versuche prüfte. GIESELER kommt zu der Schlußfolgerung :

> « Dieser Versuch und der Umstand, daß tiefe Bodenschichten im Winter wärmer sind als im Sommer, während ihm durch Kondensation gerade in Sommer latente Dampfwärme zugeführt werden müßte, läßt die von VOLGER betonte erhebliche Kondensation zweifelhaft erscheinen ».

E. EBERMAYER (7) stellte dagegen bei Lysimeterversuchen 1890 in München

fest, daß die Sickerwassermengen um 7 % höher waren als die aufgegebene Niederschlagsmenge und berechnete unter den Standortsverhältnissen von München, daß in dem Bodeninhalt der Lysimeter im Gewicht von 5,3 t 350 mm = 37 % des Jahresniederschlages durch Kondensation gewonnen worden seien.

J. Sikorski ([31]) hat nachgewiesen, daß während der Nacht Wasserdampf der Luft aus dem Boden sorbiert werden kann.

Lebedeff ([20, 21, 22]) kommt zu der Schlußfolgerung, daß in Fällen, in denen die absolute Feuchtigkeit in der Atmosphäre grösser ist als die Wasserdampfspannung in der obersten Bodenschicht, der atmosphärische Wasserdampf in den Boden eindringen und dort kondensieren muß. Lebedeff stellte bei seinen Untersuchungen im Raume von Odessa nachmittags 3 — 4 Stunden vor Sonnenuntergang 6 cm hohe und 27 — 28 mm weite Gläser, die mit Boden gefüllt waren, dessen Wassergehalt 4 — 5 % höher lag als seine Hygroskopizität, in die Erde und wog sie bei Sonnenuntergang sowie bie Sonnenaufgang. Lebedeff ermittelte so einen Kondensationsgewinn von 0,36 mm pro Tag. Bei einer Annahme von 200 Kondensationstagen im Jahr berechnet er einen jährlichen Gewinn von 73 mm.

Zunker ([45, 46]) wendet dagegen ein, daß das Glas, der Luftmantel sowie die Lockerheit der eingefüllten Erde den Wärmenachschub aus dem gewachsenen Boden erschwert haben und daß sich die Gläser infolge Strahlung unter die Temperatur der Umgebung abgekühlt haben. Er hält die Kondensationsmenge für zu hoch.

Mit einer anderen Versuchsmethodik verfolgte Lebedeff ([20]) die Kondensation im gewachsenen Boden. Er hat mit Wasser gefüllte Petrischalen in verschiedenen Tiefen in die Profilwand eingebaut und nachgewiesen, daß im Sommer eine beträchtliche Gewichtszunahme infolge der « inneren Destillation des Wassers » stattfindet.

Die Zahl der Tage, an denen im Boden Kondensation stattfand, schwankte in den Beobachtungsjahren zwischen 126 und 179. Lebedeff berechnet den inneren Niederschlag im Boden unter den Standortsverhältnissen von Odessa zu 73 mm und faßt, indem er der Schulmeinung der Hydrologen entgegentritt, seine Auffassung wie folgt zusammen : « Die Kondensation ist ein allgemeiner Vorgang und findet in allen Zonen und unter verschiedenen Bodenverhältnissen statt ». — In den gemäßigten Zonen wirken Kondensation und Infiltration vereinigt, wobei einer der beiden Vorgänge in Abhängigkeit vom Klima und geologischen Verhältnissen überwiegt.

Haedicke ([10]), Metzger ([26]), Ototzki ([28]) sind der Ansicht Volgers, daß das *Grundwasser* auf Kondensation beruht. Auch Vuisotzky ([43]) weist darauf hin, daß Niederschläge in ariden Gebieten niemals in den tieferen Untergrund gelangen, daß also das Grundwasser unter solchen Standortsverhältnissen nur durch Kondensation entstanden sein könne. Der französische Forscher Chaptal ([6]) erklärt die Bildung der Süßwasservorräte in den Küstendünen Nordafrikas ebenfalls durch Kondensation.

Kokkonen ([19]) fand während des Winters in der gefrorenen Bodenschicht eine erhebliche Wasserzunahme, während der Wassergehalt der darunterliegenden ungefrorenen Schicht stark herabgesetzt wurde. Die Vertreter der Kulturtechnik und der Hydrologie bestreiten, daß die Kondensation des Wasserdampfes in Bodem erheblich ist. So sollen nach Zunker ([45]) die « Dampfströmungen wenigstens im gemäßigten Klima keine beachtliche Rolle gegenüber der Versickerung spielen ».

Bei unseren Untersuchungen über die Kondensationsvorgänge im Boden s. Trénel ([34, 35]) und Weber ([47]) zeigte sich, daß am Tage im Boden eine Kondensation von Wasserdampf eintritt, die umso höher ist, je höher die Temperaturen der Bodenoberfläche und der Luft ansteigen. Die Höhe der Kondensation nimmt mit zunehmender Tiefe im Boden ab.

Es erfolgt eine Wasserdampfwanderung von wärmeren zu kälteren Bodenschichten, also von Orten höheren Dampfdruckes zu Orten niederen Dampfdruckes.

Das Maximum der Kondensation tritt stets zur gleichen Zeit ein wie die Maxima der Temperaturen sowohl der Luft in 1 m Höhe als auch der Bodenoberfläche selbst. Je größer die Amplitude zwischen den Temperaturkurven in Erdoberfläche und in 15 cm Tiefe ist, desto größer ist auch die Kondensation in der Krume. Wenn jedoch die Lufttemperatur unter die Temperatur des Bodens in 1 cm und in 15 cm Tiefe absinkt, dann setzt der entgegengesetzte Vorgang ein, indem die Wassermoleküle aus der wärmeren Bodenschicht in die nun kühler gewordene Atmosphäre diffundieren. Das ist während der ganzen Nacht und während der Morgenstunden der Fall.

Unsere Untersuchungen über die Herkunft des Kondensationswassers im Boden ergaben, daß die an heißen Tagen stark ausgetrockneten oberen Bodenschichten nachts und in den frühen Morgenstunden sowohl den aus tieferen Bodenschichten infolge eines Dampfdruckgefälles emporsteigenden Wasserdampf als auch Wasserdampf aus der Atmosphäre sorbieren. Eine Sorption von Wasserdampf aus der Atmosphäre erfolgt vor allem dann, wenn der von unten emporströmende Wasserdampf nicht ausreicht, die oberen Bodenschichten bis zu ihrer Hy mit Wasser zu sättigen und tritt besonders bei Stoffen mit hohem Sorptionsvermögen in Erscheinung (z.B. Na — Montmorillonit). Bei beginnender Sonneneinstrahlung erwärmen sich die oberen Bodenschichten recht schnell, der Dampfdruck steigt an und das Dampfdruckgefälle kehrt sich um. Es besteht somit am Tage von der stark erwärmten Bodenoberfläche ein Dampfdruckgefälle sowohl in die Atmosphäre als auch in die tieferen Bodenschichten.

Infolge dieses Dampfdruckgefälles diffundiert ein Teil des in der oberen Bodenschicht abdestillierten Wassers in die Atmosphäre und ein Teil des Wasserdampfes wandert, ebenfalls dem Dampfdruckgefälle folgend, in die kühlen Bodenschichten und kondensiert dort.

Die sich im Boden vollziehenden Destillations- und Kondensationsvorgänge wirken sich durch die bei der Kondensation frei werdende Wärme auf die Temperatur des Bodens aus. So stimmten z.B. bei unseren Versuchen [s. Trénel ([35])] die in der Krume gemessenen Temperaturen mit den aus dem Kondensationswasser berechneten teilweise überraschend gut überein. Für die *Erwärmung der tieferen Bodenschichten ist also nicht nur die Wärmeleitung, sondern auch die Wasserdampfbewegung von Bedeutung.*

Ferner konnten wir bei unseren Untersuchungen nachweisen, daß vom Bodenmaterial hygroskopisch gebundenes Wasser bei Temperaturen über 20° verdampft und damit wieder beweglich und physiologisch nutzbar wird.

Bei Versuchen mit Hafer, Gerste, Bohnen und Tomatenpflanzen konnten wir zeigen [s. Trénel ([35])], daß die Wurzel imstande ist, Wasser in Dampfform zun utzen; nach Erschöpfung des nutzbaren Bodenwasservorrates begannen die Pflanzen alsbald zu welken. Wenn den Wurzeln jedoch Wasser als Dampf zur Verfügung stand, blieb ihre Turgeszenz lange Zeit aufrechterhalten. So konnten z. B. Buschbohnen, deren Wurzeln Wasserdampf zugeführt wurde, 78 Tage lang bis zum Fruchtansatz aufgezogen werden, ohne daß sich Schäden bemerkbar machten.

In ariden Gebieten dürften sich die beschriebenen Vorgänge mit großer Wahrscheinlichkeit in verstärktem Maße vollziehen, da die Saugkräfte des Bodens mit abnehmendem Wassergehalt zunehmen. Es ist anzunehmen, daß in ariden Gebieten nachts und in den frühen Morgenstunden die Bodenoberfläche in besonders starkem Maße infolge des Dampfdruckgefälles sowie infolge Sorptions-, Kapillar- und osmotischer Kräfte Wasserdampf aus der Atmosphäre aufnimmt. Dieses Wasser kann dann am Tage z.T. in die tieferen Bodenschichten abdestillieren und hier den

Pflanzen sowohl als Wasserdampf als auch als Kondensationswasser zur Verfügung stehen.

Außerdem dürfte auch der während des Winters aus den tieferen Bodenschichten zur gefrorenen oberen Bodenschicht emporströmende Wasserdampf für den Wasserhaushalt dieser Böden von Bedeutung sein.

Die Bedeutung der Tatsache, daß das Wasser im Boden auch *dampfförmig* der Wurzel zugeführt wird aund zwar *schneller* als das wachsende Wurzelnetz das Bodenwasser « abweiden » kann, ist im Hinblick auf die oben erwähnten Ergebnisse für aride Gebiete ohne weiteres einleuchtend. Aber auch überall dort, wo Dürrezeiten vorübergehend auftreten, darf die günstige Wirkung des Wasserdampfes im Boden nicht unterschätzt werden.

Interessant ist in dieser Hinsicht, die von Maximow [25] besonders hervorgehobene Feststellung, daß Xerophyten in der russischen Steppe, ohne Schaden zu erleiden, Wasserverluste bis zu 30 % ihres Wassergehaltes durch Transpiration erleiden. Infolgedessen kommt Maximow [25] zu dem Schluß, daß nicht die Einschränkung der Transpiration der Pflanze durch besondere Einrichtungen, sondern die « Dürreresistenz » das entscheidende Merkmal für Xerophyten sei. Unsere Untersuchungen könnten ein Hinweis dafür sein, daß diese « Dürreresistenz » dadurch verursacht wird, daß diese Pflanzen im besonderen Maße befähigt sind, sich auch dampfförmiges Wasser nutzbar zu machen. Die von uns wahrscheinlich gemachten Gewinne von dampfförmigem Wasser aus der atmosphärischen Luft durch Kondensation gerade bei starker Sonneneinstrahlung, der Nachweis der physiologischen Bedeutung auch des Wasserdampfes der Bodenluft und das Freiwerden von Anteilen des hygroskopisch gebundenen, bisher als « tot » angesprochenen Wassers bei Sonneneinstrahlung würden erlauben, die Dürreresistenz trotz hoher Wasserdampfabgabe ohne weiteres zu verstehen.

Summary

The Condensation-Process of water in the form of vapour in natural Soil

1. During insolation water recedes in the form of steam into the cooler depths of the ground and condenses there. The amount of condensation diminishes with the depth, corresponding to the decrease of the temperature differences.

2. When the gradient of temperature is reversed, usually at night, a loss of water takes place by the flow-off of steam from the underground to the surface. During warm summer-days the daily gain of condensed water considerably surpasses the loss by distillation at night.

3. The gradient of temperature in the soil on days with dull, cool and rainy weather is not sufficiently marked to allow a measurement. These barely measurable gains through condensation will not cover the loss which took place at night.

4. During periods of clear and warm weather a considerable net gain remains in all horizons of the soil profile after the substraction of the nightly deficits of distillation.

5. The amount of condensation in the soil during fine weather periods depends upon the absolute atmospheric moisture-content. It follows that the condensation in the course of the year increases from spring to summer and decreases from summer to autumn.

6. The minimum amount of condensation is estimated to be 25 mm annually under the described local conditions. Using montmorillonite as a medium of absorption, considerable quantities of water are absorbed. Thus it may be possible that under the described local conditions with a soil containing 10 p.c. of clay a gain in absorption of 50 mm may appear.

7. Laboratory tests, in order to explain the origin of the steam, show that the steam molecules of the atmosphere diffuse into the soil.

8. Furthermore, the formation of the « inner precipitation » in these experiments depends upon the gradient of temperature, the relative atmospheric moisture-content, the active surface of the soil particles and upon the volume of soil pores.

Résumé

Des phénomènes de condensation dans le sol in situ

1. Sous le rayonnement du soleil l'eau se retire en forme de vapeur dans la profondeur plus froide en s'y condensant. La quantité de la condensation va en décroissant à la profondeur, selon la diminution de la différence de température.

2. Quand la différence de température renverse — ordinairement pendant la nuit — le sol perd de l'eau parce que la vapeur sortit à la surface.

En été, quand il fait chaud, le gain d'eau quotidien est bien plus grand que la perte produit par la distillation pendant la nuit.

3. Comme pendant des mauvais temps il ne se montre qu'une petite différence de température dans le sol, il n'y a guère des gains d'eau mesurables qui ne peuvent pas couvrir les pertes de la nuit.

4. Pendant des périodes de temps clair et chaud, un remarquable gain est de reste dans tout les horizons après le décompte des pertes causées par la distillation de nuit.

5. Pendant le beau temps la quantité de la condensation dépend de l'humidité absolue de l'air. Il s'ensuit que — en ce qui concerne le phénomène pendant toute une année — la condensation va en croissant du printemps à l'été et en diminuant jusqu'à l'automne.

6. Sous les conditions mentionées la quantité minimale de la condensation annuelle est évaluée à 25 mm. En employant du montmorillonite comme moyen de sorption, des quantités d'eau considérables ont été absorbées. On peut donc estimer que, dans un sol comprenant 10 % d'argile, un gain de sorption de 50 mm d'eau paraît possible.

7. Des essais faits en laboratoire pour résoudre la question de provenance de la vapeur d'eau, montrent que les molécules de la vapeur se trouvant dans l'atmosphère ont pénétré dans le sol.

8. Aussi dans ces essais, la formation d'une « rosée intérieure » dépend de la différence des températures, de l'état hygrométrique, de la surface active des particules de sol et du volumen des pores.

LITERATURVERZEICHNIS

(1) Alten, F. und B. Kurmies : Das Verhalten des Wassers im Boden. Handbuch der Bodenlehre. 1936, 1. Ergänzungsband, Berlin, Springer-Verlag.

(2) Beskow : Tjaelproblementsgrundfragor. Svenska Väginstitutst. 1929.

(3) Breazeale, E. L., W. T. McGeorge and J. F. Breazeale : Movement of water-vapour in soils. *Soil Science*. 1951, 71, 181-186.

(4) Briggs und Shantz : *Bot. Gaz.* 1911, 51, 210.

(5) Du Bois-Reymond, C. : Von Himmelsteichen. *Die Umschau.* 1926, 30, 945-947.

(6) Chaptal, L. : Contribution à l'étude de la rosée et des sources secondaires de l'humidité du sol. *Ann. d. l. Sci. agr. franç. et étrang.* 45e année Paris. 1928, 134-154.

(7) Ebermayer, E. : Untersuchungen über die Sickerwassermengen. *Wollnys Forsch. Geb. agr.-Phys.* 1890, XIII, H. 1/2, 11.

(8) Gieseler : Diskussionsbemerkung in « Der Berggeist ». 1878. XXIII (63), 249.

(9) Gradmann, N. : Untersuchung über die Abhängigkeit der Transpiration und des Welkens von dem Wasserhaushalt des Bodens. *Jahrb. wiss. Bot.* 1928, 69; 1929, 71, 699; 1932, 76, 558-662.

(10) Haedicke : Die Entstehung des Grundwassers. *Bayr. Industrie- und Gewerbeblatt* 1907.

(11) Hartmann : Über den waldbaulichen Wert des Grundwassers. *Mitt. Forstwirtsch. u. Forstwiss.* 1930, 385 und 1942.

(12) Hinrich, K. : Die Poppenbüller Tauteiche. Die Heimat. *Monatsschr. Nat.- u. Landeskunde Schleswig-Holsteins.* 1932, 42, 123-128.

(13) Hubbard, J. : Neolithic Dew-Ponds and Cattle-Ways. 1907, second edition, London, Zitiert aus : Thienemann : Taugewässer. *Ztschr. Ges. Erdkunde* Berlin. 1943, 219.

(14) Huber, B. : Beurteilung des Wasserhaushaltes der Pflanzen. *Jahrb. wiss. Bot.* 1924, 64, 1.

(15) Huber, B. : Xerophyten. *Handwörterbuch der Naturwissenschaften.* 1935, 2. Aufl., 10. Bd , 714, Jena, Verlag Fischer.

(16) Isert, G. : Beitrag zur Versickerung in der Gegend von Magdeburg. *Ztschr. prakt. Geologie* 1937.

(17) Isert, G. : Vertikale Bewegung des Bodenwassers mit besonderer Berücksichtigung der Rekondensation. 1937, Diss. Univ. Halle.

(18) Kausch, W. : Saugkraft und Wassernachleitung im Boden als physiologische Faktoren. *Planta* 1955, 45, 217-263.

(19) Kokkonen : Verhandlungen der VI. Kommission der Internationalen Gesellschaft für Bodenkunde Groningen, 1933. Teil B, 13.

(20) Lebedeff, A. F. : Die Rolle des dampfförmigen Wassers im Bereich der Boden- und Untergrundwässer. *Arb. landw. Meteorol.* 1913, 12, 125.

(21) Lebedeff, A. F. : Movement of water in soils and grounds. *Izvestija of the Don-Agricultural-Institute.* 1918, 3, 168-170.

(22) Lebedeff, A. F. : Proceedings and papers of the second Internat. Congress of Soil sci. Leningrad-Moscov, USSR, 1930, VI. Bd., 66.

(23) Mägdefrau : Untersuchungen über die Wasserdampfaufnahme der Pflanzen. *Ztschr. Bot.* 1931, 24, 433.

(24) Mägdefrau und Wutz : Die Wasserkapazität der Moos- und Flechtendecken des Waldes. *Forstwiss. Zentralbl.* 1951, 70, 103.

(25) Maximow, N. A. : Physiologisch-ökologische Untersuchungen über die Dürreresistenz der Xerophyten. *Jahrb. wiss. Bot.* 1923, 62, 128.

(26) Metzger : Die Dampfkraft als Ursache der Grundwasserbildung. *Gesundh.-Ing.* 1906, 14, 569.

(27) Olbertz, M. : Über die am Standort des Kulturbodens erfaßbaren Größen des Wasserhaushaltes. 1955, Habilitationsschrift Landw.-Gärtn. Fak. Univ. Berlin.

(28) Ototzki : Das Grundwasser, sein Ursprung, seine Bewegung und seine Verteilung. *Petermanns Mitt.* 1932, 215.

(29) Sachs, J. v. : Handbuch der Experimentalphysiologie der Pflanze. 1865, Leipzig.

(30) Schratts : Wasserhaushalt der Pflanzen in den Trockengebieten von Arizona. *Jahrb. wiss. Bot.* 1931, 153.

(31) Sikorski, J. : Untersuchungen über die durch die Hygroskopizität der Bodenarten bewirkte Wasserzufuhr. *Forsch. Geb. Agr.-Phys.* 1886, 9, 421.

(32) Suring, R. : Die Wolken 1950, 3. Aufl., Leipzig.

(33) Torstensson, G. : Über den Einfluß der Bodenbedeckung. Verhandlungen der IV. Kommission der Internationalen Gesellschaft für Bodenkunde in Königsberg 1929. 1930, Berlin.

(34) Trénel, M. : Zur gutachtlichen Beurteilung des Einflusses der Grundwasserabsenkung auf den Ernteertrag im Löß, *Ztschr. Pflanzenern., Düng., Bodenk.* I. Mitt. 1949, 45 (90), 133-147; II. Mitt. 1950, 49 (54), 25-59; III. Mitt. 1950, 49 (94), 224-237.

(35) Trénel, M. : Über Kondensationsvorgänge im Boden. *Sitz.-Ber. Dtsch. Akad. Landwirtsch.-Wiss.* Berlin 1954, III, H. 6; 1955, IV, H. 14, Leipzig, Hirzel-Verlag.

(36) Ulrich, R. : Untersuchungen über die Wärmekapazität der Bodenkonstituenten. *Forsch. Geb. Agr.-Phys.* 1894, 17.

(37) Ursprung, A. : Der Wasserhaushalt der Pflanzen, *Handwörterbuch der Naturwissenschaften.* 1935, 2. Aufl., 10. Bd., S. 548, Jena Verlag Fischer.

(38) Vageler, P. : Der Kationen- und Wasserhaushalt des Mineralbodens. 1932, Berlin, Springer-Verlag.

(39) Vatter, H. : Eine Grundwasserstudie im Lößgebiet des Sundgaues. 1919, S. 8, Stuttgart.

(40) Volger, G. H. O. : Bodenthau und Bergschweiß. In : Erde und Ewigkeit. 1857, S. 202, Frankfurt/Main, Verlag Meidinger Sohn & Comp.

(41) Volger, G. H. O. : Die wissenschaftliche Lösung der Wasser-, insbesondere der Quellenfrage. *Ztschr. Ver. dtsch. Ing.* 1877, 21, 481.

(42) Volger, G. H. O. : Über eine neue Quellentheorie auf meteorologischer Basis. *Meteorol. Ztschr.* 1887, 4, 388.

(43) Vuisotzky : Hydrological and geobiological observations in Veliko-Anadol. Potschwowedenije 1899, 39; zitiert aus Proceed. and papers of the I. Internat. Congr. of soil sci., 2. Teil, S. 494.

(44) Walter, H. : Die Anpassungen der Pflanzen an Wassermangel. Die Wasseraufnahme bei Xerophyten. *Naturwiss. u. Landwirtsch.* 1926, 9, 40.

(45) Zunker, F. : Das Verhalten des Bodens zum Wasser. *Handbuch der Bodenlehre.* 1930, Bd. VI, 66-220, Berlin, Springer-Verlag.

(46) Zunker, F. : Verhandlungen des II. Internationalen Kongresses für Bodenkunde, Moskau, Komm. VI., S. XVII u. S. 94.

(47) Weber, Heinz : Über Kondensationsvorgänge im gewachsenen Boden. *Dissert. Wissenschaftliche Zeitschrift* der Humboldt-Universität zu Berlin Mathematisch-naturwiss. Reihe. Nr. 6 Jahrg. IV. 1954/55 S. 541-580.

TOME II

EAUX SOUTERRAINES

SYMPOSIUM SUR L'INFLUENCE DE LA VÉGÉTATION SUR LE CYCLE HYDROLOGIQUE

SYMPOSIUM SUR LA ROSÉE ET LES CONDENSATIONS OCCULTES

(31882) Etablissements Ceuterick, s. c., 66, rue V. Decoster, Louvain
Resp. L. Pitsi, 25, rue Dagobert, Louvain (Belgique.)

Imprimé en Belgique. PRINTED IN BELGIUM